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UXO FORUM 1996

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March 26 - 28, 1996
Williamsburg, Virginia

UXO FORUM 1996
Conference Proceedings

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UXO FORUM 1996
Williamsburg, Virginia
26-28 March 1996

Dear Conference Attendee:

On behalf of the Department of Defense Explosives Safety Board (DDESB) and the other conference host and sponsor organizations, I want to thank you for attending the UXO FORUM 1996. I hope that the conference met your expectations and you gained a greater understanding of the issues associated with unexploded ordnance (UXO). Because of your participation, the conference was a great success.

I feel that the objective of the conference -- to draw together a diverse, worldwide audience to exchange information related to UXO issues -- was met. Over 450 people attended the conference; an extensive exhibit session aided in information exchange and provided additional networking opportunities.

A complete listing of conference attendees and the manuscripts for the conference presentations are included in these proceedings. If you need additional information about a particular manuscript, please contact the presenting author at the address and telephone number provided in the manuscript. If you require additional proceeding copies, contact Ms. Kelly Enwright at PRC Environmental Management Incorporated at (513) 241-0149.

Again, thank you for your participation in the UXO FORUM 1996. I look forward to your continued participation in upcoming UXO conferences.

Sincerely,

W. RICHARD WRIGHT
Colonel, USA
Chairman

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ACKNOWLEDGMENTS

The UXO FORUM 1996 was coordinated by PRC Environmental Management, Inc., for Kelly Rigano [(410) 612-6868], Program Manager, U.S. Army Environmental Center (USAEC), Aberdeen Proving Ground, Maryland under Contract No. N00174-95-D-0009 with Gerard Snyder, [(301) 743-6855] Director, UXO Clearance Technology Program, Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), Indian Head, Maryland. Special appreciation is given to the Department of Defense Explosives Safety Board for sponsoring the UXO FORUM 1996 and to USAEC for hosting the conference. The UXO FORUM 1996 was coordinated in cooperation with NAVEODTECHDIV, U.S. Air Force/Wright Laboratory, U.S. Army Corps of Engineers, Huntsville Division, U.S. Army Project Manager for Non-Stockpile Chemical Materiel, and the Western Governors' Association.

UNIQUE MAN-PORTABLE 5 ELEMENT FLUXGATE GRADIOMETER SYSTEM

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ABSTRACT

Demilitarization activity currently underway will allow the return of large tracts of land to the private sector. It is imperative that all energetic materials be located and removed before release of land to the public. A large percentage of this material such as bomb shells, steel drums, etc., are characterized by significant ferrous content and can be detected by magnetic sensors. As a result of their vector nature, conventional fluxgate magnetometers are able to both detect and localize magnetic targets, but in the past, motion noise caused by their movement in the earth's magnetic field has limited their utility to stationary applications.

The Navy's Coastal Systems Station teamed with IBM, Yorktown has developed a hardware solution which, when coupled with software algorithms, allows the use of inexpensive fluxgate magnetometers to collect high quality real time localization data while the sensor system is in motion. This technology breakthrough was accomplished by connecting three, three-axis magnetometers to form a series of three sensor magnetic gradiometers. A helmholtz feedback coil system is used to both increase the systems dynamic range and reduce motion noise. A fourth three-axis magnetometer is used as a reference sensor to generate feedback currents that place each of the other magnetometers in a nominally zero-field state. This forces all output voltages to very near zero voltage under the condition of zero magnetic gradient. The required accurate and sensitive magnetic gradiometric differences may now be accurately derived even in the presence of very large magnetic fields. Coupled with newly developed software algorithms, significant real time detection and tracking capabilities have been demonstrated against ferrous targets of all types.

This technology has many applications in areas where other technologies are limited, such as for buried objects, including those underwater and targets that are obscured from visual detection. As this sensor provides realtime precision localization information, it makes an ideal candidate for sensor fusion with other technologies in order to enhance detection and reduce clutter.

While the tracking fluxgate gradiometer is still in the prototype development stage, the technology has no technical barriers that would prevent it from rapidly evolving into a small, fieldable, man-portable system. The advantages of this technique include its simple, low cost implementation and its applicability to a wide variety of targets and scenarios. Several application areas will be reviewed and the limitations of the technology discussed. The utility of this technology has been demonstrated by a hardware prototype funded by Special Operations Command (SOCOM) and designed for Navy diver applications. The Army Corp of Engineers also instituted a task to apply the SOCOM prototype to land based UXO applications.

INTRODUCTION

In the past, the best magnetic sensors have only been able to detect the presence of hidden ferrous objects. They could not determine the precise target location without being swept across the suspected area in an elaborate grid mapping pattern and only then with extensive processing of the output data. Fluxgate magnetometers have had high noise levels while in motion because of their inherent vector nature and have thus been limited to stationary applications. They are relatively small and inexpensive compared to other magnetic sensors. Many additional potential uses and applications for fluxgate magnetometers would be generated if their inherent motion noise could be eliminated. The tracking fluxgate

gradiometer design allows the application of fluxgate technology to mobile applications by configuring the fluxgate magnetometers as gradiometers and operating them in a nominally zero field condition. The prototype gradiometer, while providing proof-of-principle, is presently limited in it's operational utility due to both its non-miniaturized size and thermal drift, both of which appear correctable. The gradiometer can be engineered to fit into a small notebook computer sized package, while the implementation of internal magnetic feedback with current source electronics would eliminate its temperature sensitivity. After successfully completing the proof of principle demonstration within the SOCOM program, the prototype tracking fluxgate gradiometer was adapted to provide proof of concept information to the Corp of Engineers, U.S. Army for the mapping of UXO targets.

In the past, fluxgate magnetometers have been limited to stationary applications due to their vector nature. Because of its small relative size and cost, many additional potential uses and applications for the fluxgate magnetometer would be generated if this inherent motion noise could be eliminated. This paper describes a unique hardware solution that when coupled with a set of robust software algorithms, would allow the use of inexpensive fluxgate magnetometers to collect high quality data even when the sensor system is in motion. A novel three sensor gradiometer configuration patented by IBM makes this noise cancellation possible. When coupled with appropriate algorithms, significant detection and target tracking capabilities have been demonstrated. This technology has obvious advantages and applications in areas where other technologies are limited, such as buried objects including those underwater and targets intentionally hidden or obscured from visual detection. While the sensor system is still in the prototype development stage, the described techniques and technology are expected to ultimately make a small, fieldable, man-portable, tracking gradiometer a reality. Advantages of this technique are its simple implementation and wide applicability to a variety of targets and scenarios. Early test results from the first diver prototype system are presented. Several potential areas of application are reviewed, and the technological advantages and limitations discussed.

THEORY OF OPERATION

The Room Temperature Gradiometer (RTG) system takes advantage of conventional analog sensors coupled to the power of digital signal processing. As shown in Fig. 1, the hardware is made up of three major groups; 1) the basic sensor array, 2) the analog interfacing electronics, and 3) a digital computer equipped with an Analog to Digital (A/D) converter card. Analog technology is used to both generate and implement the magnetic feedback currents required for motion compensation. However, the precision of digital processing is applied to this process by digitally calculating each of the 27 required feedback adjustments which are then manually set. The software calculates each adjustment with 5 decimal accuracy. The remaining signal processing, diagnostic and display routines systems are digital. Each major group will be discussed individually starting with the sensor package.

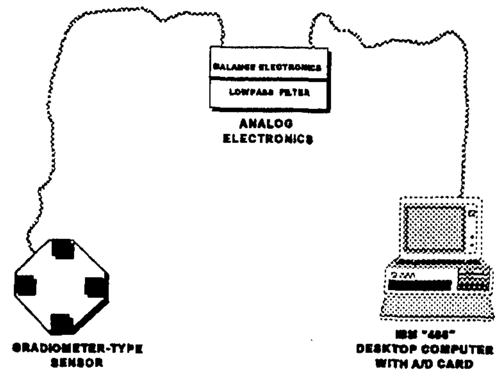

Fig. 1. Major components of the tracking gradiometer system

Sensor technology

There are basically two types of magnetic sensors; total field and vector or component. The total field sensor, as the name implies, senses the total magnetic field that passes through its sense volume. It can provide a sensitive and accurate absolute measurement of the magnetic field intensity, but provides no inherent directional information as to the source direction of that magnetic field. This feature is used to advantage in a moving sensor system that must constantly change direction. The vector nature of a component magnetometer, such as the fluxgate, on the other hand, make it very sensitive to change in orientation. If used as an orthogonal, 3-axis triad set, it provides the absolute magnitudes of the three spatial field vectors. These three vectors can then be combined into the resultant field magnitude complete with its associated angular relationship within the sensors coordinate system. Because of this acute sensitivity to direction, this type of magnetometer has in the past, been restricted to stationary applications or was useful as a compass when in motion. It had no capability to detect small magnetic targets when

in motion. If, however, two or more of these orthogonal sensor packages were rigidly mounted with respect to each other and precisely aligned, the corresponding vector outputs could then be subtracted, and the resulting gradient output would not be sensitive to motion as both sensors would experience identical changes in a uniform magnetic field. This, in general, is the approach taken in the tracking fluxgate gradiometer as described in this paper and shown in Fig. 2. In the past, there have been several inherent limitations to this approach. First it is very difficult to extract the accurate difference of two relatively large voltages with a high degree of precision. This problem will be addressed in the next section under 2.2 Analog electronics. Second, practical constraints limit the mechanical balance to around 1 degree. Under worst case conditions this would produce an imbalance signal of around 30 nanotesla when rotated perpendicular to the earth's field thus limiting sensitivity to this level when in motion. In addition to the precision alignment requirement, two other related factors play an important role in how well the sensor is able to perform under actual operating conditions. The first factor is the stability of the mounting, since even the smallest of changes in angular relationship between the two gradiometric sensors produce rather large output signals. This problem is further compounded whenever the system is in motion by the detrimental effect of the permanent imbalance resulting from a permanent shift in relative orientation.

In the first prototype design, to assure that this change in deformation was minimal, a bulky baseplate of 2" macor-type material was selected, with the intentions of investigating lighter materials and construction at a later time. The Macor, being of a ceramic nature, is very rigid

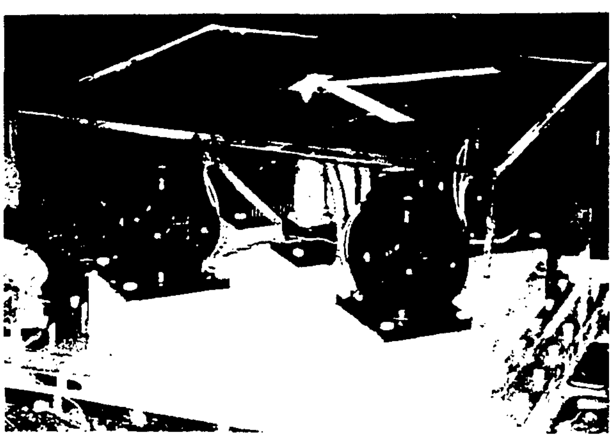

Fig. 2a. Photo of prototype sensor array

and exhibits little deformation with temperature changes. Later prototype designs could be compared with the performance that was achieved with the more massive baseline system. The second factor that has caused problems in the past as sensitivities are pushed toward higher limits, is the inherent temperature dependence of

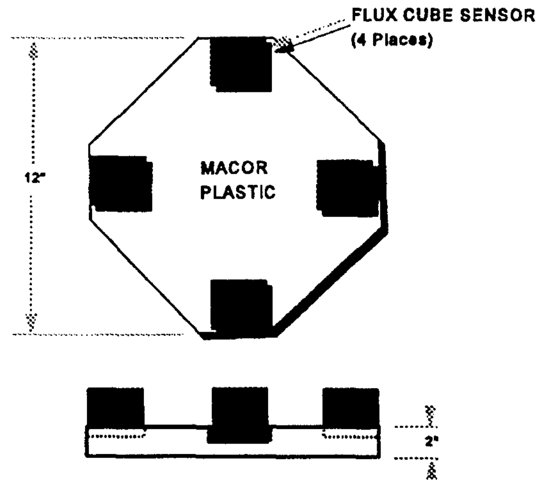

Fig. 2b. Outline drawing showing the location of individual fluxgate sensors

the basic fluxgate magnetometer. The source of this temperature drift is thought to be inherent within the core of the sensor, but also could have limited contribution from the copper windings on the core. Because of the gradiometric connection of the sensors some of this temperature driven drift will be canceled in the present configuration provided that all the sensors involved experience the same temperature stimulus. Achieving absolute temperature uniformity at each sensor site is very difficult, especially when different parts of the sensor array are exposed to unequal heat loads such as sun/shade conditions or wind loading. To enhance the performance of the current prototype, the entire sensor array has been encased with a plastic shell and the interior lined with 1" Styrofoam insulation.

Analog electronics

Overview

A detailed block diagram is included as Fig. 3 to illustrate the analog operation of the Room Temperature Gradiometer system (RTG). The complete sensor array originate twelve channels of magnetometer data. These channels are then connected to commercial companion electronics by a manufacturer installed, 50 foot sensor cable. Utilizing this cable allows the use of remotely

located, commercial, ac powered electronics without sensor degradation. Nonmagnetic electronics will be designed for final version and collocated with the sensor. This remote sensor electronics provide the required drive signals for the fluxgate and also some low noise amplification and conditioning before handing the output off to the system. Electronic circuitry collocated with the commercial conditioning electronics generate the required magnetic feedback for each sensor by feeding back carefully adjusted amounts of the three outputs from the reference sensor. The magnetically related outputs from all twelve magnetometer channels are then transmitted approximately 75 feet to the instrumentation hut where they are lowpass filtered at 3 Hz and a 20 dB boost is given to the nine compensated channels. This additional gain is made possible because of the magnetic feedback[1] being generated through the reference sensor and applied to each helmholtz pair which removes the large offset caused by the earth's ambient magnetic field. At this point the twelve magnetometer signals pass through the computer's A/D for further digital processing, final display and recording.

Detailed circuit analysis

After the initial signal cancellation obtained on the sensor array through careful mechanical alignment, electronic feedback technology will allow a further 40 to 60 dB reduction in imbalance signal. Using a patented technique developed by IBM[1], motion related signals in the output are reduced by applying appropriate feedback to the external helmholtz coils wound around each sensor. The basic concept for a single channel is shown in Fig. 4.

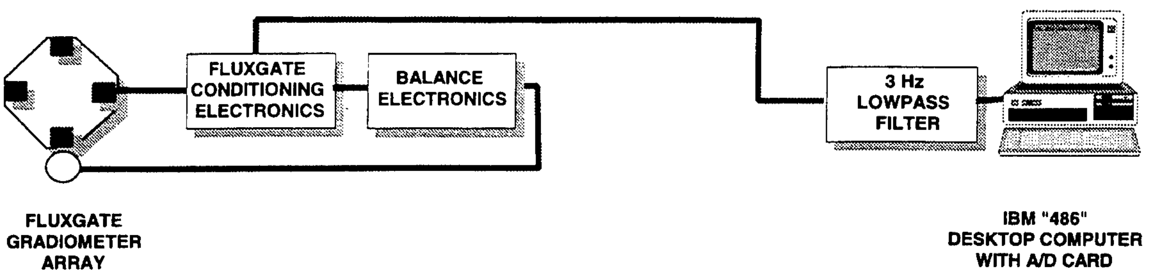

Fig. 3. RTG system block diagram

Basically a third sensor, in addition to the normal gradiometer pair, is used to determine the ambient magnetic field condition that exists around the gradiometer. Its output is then used to drive the coils around the gradiometer pair to produce a counter field proportional to the one experienced at the reference position. This will then place the two gradient sensors in a nominal zero field condition when the array is exposed to a uniform magnetic field, thuseliminating the large dynamic range requirements of a normal fluxgate gradiometer operating in the earth's magnetic field. Very accurate imbalance differences then can be extracted since both sensors are operating on the identically same portion of their linearity scurves. Their outputs may now be subtracted directly, with gain, if desired, and without any stringent offsetting. In the current prototype, the exact amount of feedback current required for each sensor is determined by sampling all magnetometer outputs with the sensor in three axis motion and allowing the computer to determine the amount of noise contribution caused by each magnetometer. After processing a three minute segment of motion data the computer generates a printed form indicating the present degree of balance or

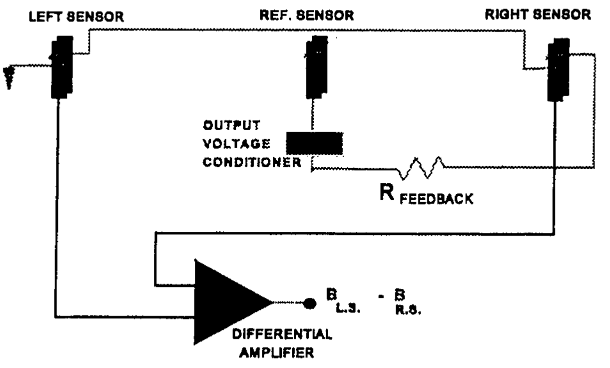

Fig. 4. IBM's patented, 3 sensor gradiometer[1]

with the necessary degree of precision, the pots are locked into place and readjustment is not required under normal conditions.

For convenience and to avoid the potential of any magnetic noise that the balance pots and associated ac powered circuitry might produce, the balancing electronics was located as far as possible from the sensor, at the end of the manufacturer-attached, fifty foot sensor control cables. **It should be noted that in the first prototype three distinct groupings of equipment exist both to simplify and expedite system fabrication. This test-bench brassboard configuration allowed the use of readily available components that while able to perform the required functions, were neither nonmagnetic nor miniaturized. Later versions will be battery operated and locate all functions together.** The individual outputs from all 12 magnetometer channels were passed through this intermediate location. The three reference magnetometers outputs were tapped and converted to appropriate feedback currents, and returned through individual shielded pairs to the proper helmholtz feedback coils on the sensor array. All twelve magnetometer channels were then connected through individual coaxial cables to processing instrumentation located an additional 70 feet away from the sensor. Here they were lowpass filtered at 3 Hz. and additional gain was inserted into the nine corrected magnetometer channels before being converted into digital data. It should be noted that to avoid saturation problems, this gain can only be added after reasonably good compensation is achieved. There is no digital communication required between the three locations.

Digital electronic processing

The twelve analog outputs from the magnetometer array, after passing through the lowpass filter were digitized via a 12-channel, 16 bit A/D board located within the IBM 486 computer. The digital capabilities of the computer were thoroughly exploited by generating a full complement of diagnostic and detection/localization software. The system is entirely self sufficient without the requirement for additional test/evaluation circuitry and equipment. Some of the most useful programs and routines provided are briefly described in the following text.

DMCHART is a routine which displays the operators choice of magnetometer or gradiometer outputs, either "raw" or corrected. It is an autoscaling program that allows operator independent selection of many parameters such as; timebase, channel assignment, and ac/dc response. A second program, ADJBAL provides the precision pot setting values for each of the 27 individual balance pots as well as the level of current balance and rate of closure. The operation of this program is dependent on another program called MEABAL which can be called independently to indicate current balance conditions. Still another routine called MEANOI is used to determine the Power Spectral Densities (PSD's) for each of the magnetometers and gradiometer channels.

There are several variations of the primary routine used for the actual operation of the sensor. Basically they are similar in operation but enable different display and processing capabilities dependent upon current applications. To operate the system in a barrier mode a routine named TRACKOS2 would be called. To search for buried targets SEARCH would be used. The final version may not offer a mode choice in the field. With the call of the operating macro no further adjustments are required to begin operation. At the present state of development it appears that for extended operating periods a push-button switch would be required to periodically rezero the gradient outputs. Exact need and procedures are undefined at this time and the requirement may be eliminated through further hardware/software development. The current display for the tracking program TRACKOS2 consists of four windows or views on the CRT. The first view is the sum of the corrected gradiometer channels providing an indication of target signal strength. Ideally it should be near zero, system noise, when no targets are within range. It can be used as a preliminary indicator providing early detection alert. At this stage in development it is used to determine when to reset the outputs due to system drift. The other three windows are required for providing a three dimensional track history. The "PLAN" shown in the second window on the upper right of the CRT is the most useful since it actually points toward target location giving two dimensional range and bearing information. At this stage of development the two lower windows are used to track elevation. While other methods could be used to present elevation, this method was selected to provide track history that may be required in certain applications. **The current prototype does not compute the targets magnetic moment magnitude. It is preprogrammed for a certain range of magnitudes depending upon application. This makes it somewhat selective and most accurate only for the targets of interest.** It does compute the moment vector angle on a point by point basis allowing for real time tracking of either stationary or moving targets.

When operating in the SEARCH mode it is helpful to have only a single window on display which is able to provide two dimensional range and bearing information

only, with all ancillary data such as relative elevation and signal magnitude being provided by numerical readout and with no prior history. A magnet moment indicator may also be useful but not implemented in the present version.

PROTOTYPE EVALUATION

Diagnostic characterization and balancing

The system as received from IBM was evaluated under the controlled magnetic conditions of the Nonmagnetic Facility of the Coastal Systems Station. Field evaluation of the prototype system was begun with several series of balance measurement tests and balance iterations. Before collecting target data, the system was both characterized and balanced. Characterization verified the sensitivity, calibration and orientation of each gradiometer channel. This was accomplished through the use of a calibrated magnet that was precisely positioned at cardinal measurement points. Using the known magnetic moment of a calibration magnet, all measured sensitivities were within 5 percent of the theoretically predicted. Since the basic fluxgate sensor is a vector or component sensor, it is very critical that the gradiometric pairs be balanced with precision. As mentioned earlier in section 2.2, balancing or compensation was effected by the manual adjustment of 27 individual pots. Initially they each pot was set to midrange representing no applied compensation. The DMCHART program was run and the twelve magnetometer outputs displayed to verify proper operation. After this was ascertained, the program ADJBAL was run. A copy of the printout generated by the ADJBAL software is shown as Fig. 5.

#	POTSET	BALANCE
1	4.93484	-0.0235968
2	4.92189	-0.0077053
3	5	-0.000760476
4	4.73856	-0.0310674
5	4.37646	-0.310725
6	5	0.000951785
7	5	-0.000458377
8	6	0.0183518
9	4.94701	-0.0125901
10	4.90851	-0.0371884
11	5	-0.00072032
12	5	-0.000996214
13	4.69258	-0.0227894
14	4.41016	-0.301567
15	5	9.04148E-05
16	4.96174	-0.0083756
17	5.4212	0.0189911
18	4.91695	-0.0198443
19	4.95765	-0.0167672
20	5	0.000295701
21	5	0.000174424
22	4..83748	-0.0126457
23	4.41736	-0.285322
24	5.07063	0.00674111
25	5	0.000208454
26	5.47448	0.0113545
27	4.92551	-0.0177878

Fig. 5. Sample balance printout with no applied compensation

From this printout, the initial mechanical balance of the system can be inferred. Since each pot is set for midrange, no feedback correction is being applied. The column entitled BALANCE[then indicates the raw mechanical balance of each of the nine magnetometers in both its primary and secondary directions. Mechanical balance can be seen ranging from around 0.3 to 0.0001. By applying appropriate amounts of magnetic feedback calculated by the processor, the balance as shown in Fig. 6 was eventually achieved.

#	POTSET	BALANCE
1	4.67738	0.000735453
2	4.84125	0.000280884
3	4.94778	0.000617693
4	4.30205	-0.00153826
5	1.98126	0.00321569
6	4.92505	-4.30138E-05
7	4.75018	-0.00320338
8	5.36233	0.00199966
9	4.7932	0.00108015
10	4.58004	0.00161232
11	5.03563	0.00011285
12	4.94702	0.000620739
13	4.09752	0.000457585
14	2.14712	0.000821815
15	4.89372	0.00033206
16	4.65918	-0.00316178
17	5.57676	0.00167269
18	4.63414	0.00038109
19	4.78007	0.000960288
20	5.08712	0.000602479
21	5.00657	0.000448946
22	4.30897	0.000111954
23	2.26556	0.00069442
24	5.14535	-2.6131E-05
25	4.76799	-0.00378822
26	5.57905	0.00209156
27	4.72521	0.000791965

Fig. 6. Sample balance printout after feedback compensation

A minimum of 30 adjustment cycles were required to obtain the degree of feedback compensation necessary to enable data collection with the system in motion. This was a rather time consuming process in that the ADJBAL program was run thirty times and printed 30 sets of printed adjustment requirements that had to be manually set into the 27 feedback pots for each data set. The ADJBAL software requires that the sensor be placed in motion about the three cardinal axes for a period of approximately 3 minutes while the computer is collecting the database. While not required by the software, it was found convenient to use a 3 axis motion table to generate the required motion during this phase of testing. By referring to Fig. 6 it can be seen that the balance improved to the point that all were below 0.003 and most were improved an order of magnitude. This means that for any given angular motion, the compensated output would be reduced by the balance number over that which would be generated by an uncompensated magnetometer. These compensated magnetometer outputs were then digitized and appropriately subtracted into the five required gradiometer channels. These gradient channels were then corrected by the computer to enhance the gradient

by another two to three orders of magnitude, resulting in final gradiometer balance approaching 1 part in a million or a balance of 10^{-6}. While there has been no opportunity to determine the degree of balance drift with time, the system appears to hold reasonably well over a one-month periods without requiring adjustment.

After completing the balance/compensation phase of the evaluation, a diagnostic software program called MEANOI was run to determine overall sensor performance with frequency. This was accomplished by generating Power Spectral Density (PSD) plots of each gradiometer output. A sample PSD for each gradiometer channel is included as Fig. 7. The performance goal for each was 0.1 nanotesla at 0.1 Hz and above. This is the straight horizontal line drawn on each plot at the 0.01 nanotesla ^{2} level. The system clearly demonstrates performance better than the design goals.

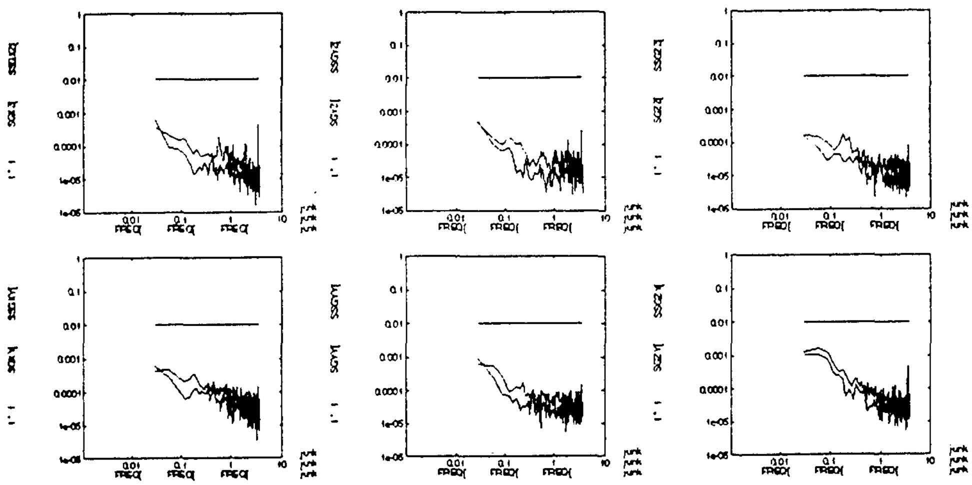

Fig. 7. Power Spectral Density plots for the six gradiometer channels

System evaluation has uncovered rather large temperature sensitivities in all channels. Since this drift was not observed initially in the magnetometers, it has been deduced that it originates in the magnetic feedback circuitry. More specifically in the copper windings that constitute the sensor feedback coils. Since their resistance changes with temperature, the current flowing through them also change along with a corresponding change in the magnetic field they produce. Unequal heating will then produce large drifts in the gradient outputs and hence errors in localization accuracy.

Operational performance

Two distinct modes of operation have been developed, track and search. The first mode is a TRACK mode where the sensor array is being used in a barrier surveillance scenario and it is desired to track magnetic penetration within that barrier. This barrier may either be a fixed geographical position or moving platform.

Using the system in the TRACK mode, illustrated in Fig. 8, it is helpful to develop the track history in three dimensions. A screen display of four windows is utilized. The first window in the upper left plots the magnetic detection signal strength (sum of magnetic moment vectors). It is useful in early detection of potential penetration and also as an indicator of system

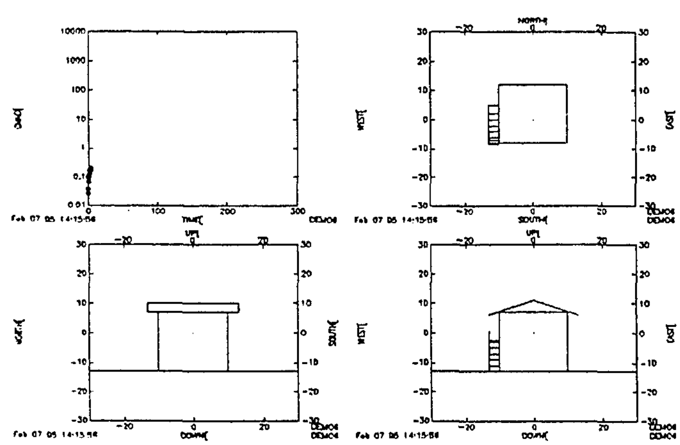

Fig. 8. Operator display format used for the TRACK mode (barrier application)

performance. The second window on the upper right hand side of the screen is a plan view with the sensor located in the middle of the window. It may be considered a view from directly above the earth looking down. The third and forth windows at the bottom of the display are used to track the target in both position and elevation. This type of display is useful in preserving track history for the operator. The utility of the display as well as system capability is illustrated with the track shown in Fig. 9.

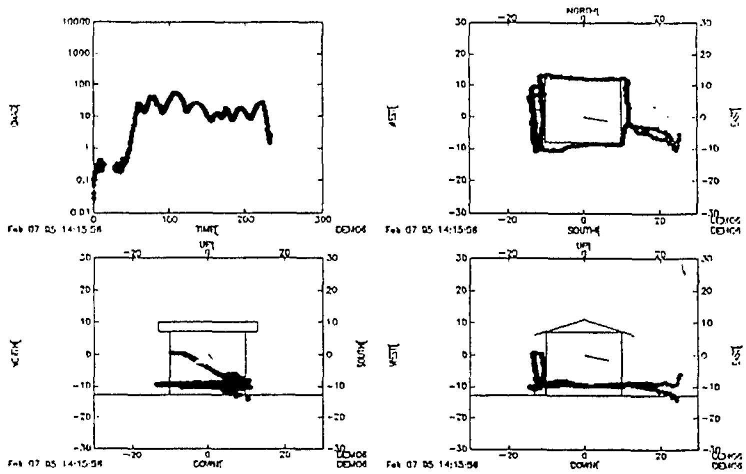

Fig. 9. Sample of track history and system precision when operated in TRACK mode

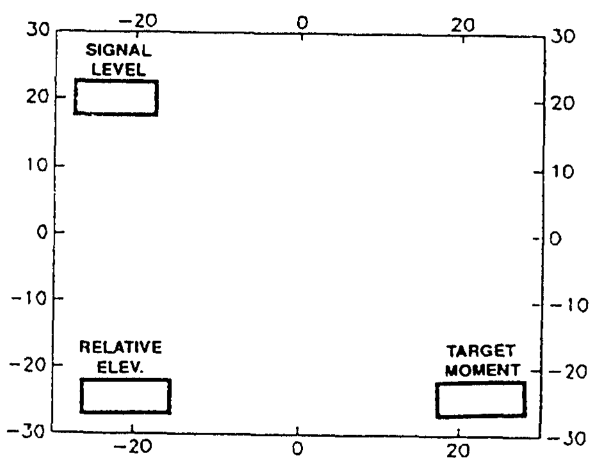

Fig. 10. Single window display used in SEARCH mode

For purposes of illustration a simple drawing of the test building housing the sensor was drawn on the display. Both the building and scaled drawing were very useful in establishing the system resolution and the repeatability of tracks. The sensor array was located on the second level of the building to simulate conditions of a diver searching for buried mines. In this case the target was tracked around the sensor illustrating the barrier mode of operation. The track began and ended on the far right side of the "plan" view, proceeded to the building wall and then followed wall down and to the left to the stairs, up the stairs against the wall and then across to outer stair rail, down the stairs and up around the stairs on the ground level, going under platform at top of stairs and then following building wall all around to the point of entry. Elevation changes are easily seen in both lower "side" views and track resolution are illustrated on the trip up and down the three foot wide stairway.

The second mode of operation is the SEARCH mode. This is the more common mode of operation for the location of lost and buried ferromagnetic targets. The current display, as shown in Fig. 10, consists of a single window showing the plan view. This window has three active inserts. One indicates the elevation of any detected targets relative to the sensor while the second indicates the sum of the gradient moments. The third insert will show the calculated moment of the detected target.

FUTURE REFINEMENTS

The present prototype system could be modified to make it a self-contained, man-portable, land based magnetic detection/mapping system capable of finding both small and large targets within its detection range. This could be done simply by repackaging the sensor into suitable form for the application and tethering it to the current processing equipment mounted on a nonmagnetic platform. Since it would still be ac powered and consist of large components, it would not be man portable nor optimized for any particular application. While it is possible to modify the existing prototype system to an appropriate configuration with the moving sensor tethered to the ac powered support electronics and tracking computer, it would not be possible to make it truly one-man portable without extensive redesign. A more ambitious program would include; miniaturizing the processing electronics, expanding the software capability

to handle multiple targets, and providing the required position sensing capability to enable automated mapping. This would include both sensor and electronic miniaturization, replacement of the desktop with a laptop computer and packaging for single-person operation. The current fieldable prototype system, while being able to detect and track magnetic targets, is still an ac-powered system tied to a desktop 486 computer. At its present stage of development, only the sensor package is fitted with an underwater housing. Ultimate applications require a system, including sensor, electronics package and battery , that occupies less than a cubic foot of volume and weigh under 15 pounds. The following suggestions are directed toward making the current fieldable prototype, a fully fieldable, man portable detection/location system capable of detecting a wide variety of magnetic targets, including multiple contacts at ranges suitable to the application.

The current prototype has little or no discrimination against multiple targets within its detection range and these must now be handled by operator deductions. It has potential for increased coverage rates due to standoff localization technology. In addition, operator safety is enhanced due to this standoff localization. With the addition of GPS and/or other position determining capability, the system could provide a unique ability to map in real time. It could also provide the ability to vector either itself or a remotely controlled platform directly to mines and other targets with a high degree of accuracy. (It does not, however, provide any significant capability against targets having little or no magnetic properties, and should be fused with other technologies such as GPR (or sonar if appropriate) and electro-optics for applications where such risks occur.)

Enhanced sensor array

Sensor improvements that should be considered are, the fabrication of a full 5-element tracking gradiometer system specifically designed for land applications and man-portable operation. The current external feedback coils will be replaced with direct internal magnetic feedback injected directly into the core of the commercial magnetometer. The sensor system would be designed to operate on the existing data collection system. This enhancement would reduce current sensor volume by a factor of four, greatly reduce or eliminate the magnetic signature and improve temperature stability as well as magnetic balance. This fabrication would consist of both the sensor package and balance electronics. An effort of this nature is estimated to require a 1 year period and would reduce both size and power requirements as well as increase temperature stability and balance characteristics of the system.

Electronic miniaturization

The commercial analog filter bank should be replaced by a custom-design miniaturized and nonmagnetic subassembly. The processing and display functions should be transferred from a desktop 486 computer to a laptop or belt mounted computer for enhanced portability. This task would reduce both power requirements and size.

The 27 balance pots should be replaced with computer driven MDAC modules to completely automate the balancing process. Again miniature, nonmagnetic components should used to enhance the small single unit concept. This enhancement would allow rapid and easy rebalancing in the field should the need arise. This effort would improve operability and decrease overall size.

Software development

Many potential applications require the ability to discriminate between multiple targets. The current prototype is limited in being able to do this and a robust multi-target tracking capability should be developed. The fact that magnetic signatures decrease as the forth power (r^4) of range when using gradiometer detectors which, in the past, has greatly limited detection range, might now be used to great advantage in multiple target discrimination since the closest targets would produce the greatest signal change contribution for sensor motion. The very rapid reduction in signal with range ($1/r^4$), within itself, not only greatly reduces the probability of multiple contacts, but also tends to reduce the error that is introduced when such situations do occur which provides a degree of discrimination. This effort should develop proper software/operational tactics to allow selective localization in the presence of multiple magnetic targets. The process should require only minimal operator interaction. This effort improves operability and should increase PD's.

The newly developed CSS "rate sensitive" magnetic tracking algorithms[6] should be investigated for improved tracking capabilities and the elimination of multiple solution "ghost" problems.

Expanded capability

An automated mapping and remote platform vectoring capability may be required for future applications.. This effort would require the addition of GPS and/or other position locating hardware and developing the required software for integration into the magnetic data stream.

Since most of the required hardware and software is off-the-shelf, only very simple modifications are required.

Hardware customization

Packaging and form fitting the system to man-portable form involves not only the placement of equipment, but also developing the capability to operate in harmony with potentially interfering signals which are present on the host platform (primarily magnetic). This is a six month effort and addresses operability.

SUMMARY OF MAJOR ADVANTAGES

The RTG prototype funded by Special Operations Research, Development Command (SORDAC) and developed jointly by the Coastal System Station and Loral/IBM circumvents current magnetic sensor limitations by providing the capability of tracking ordnance (500lb bomb) at standoff ranges up to 30 feet and with a resolution of approximately 1 foot. It does not require grid search patterns nor cryogenic logistics. It is not sensitive to RFI and may be operated in close proximity to many electrical/electronic subsystems. The current system prototype will provide standoff detection at reasonable sweep rates with potentially high PD's against other targets of interest having only minimal magnetic signatures. It is capable of tracking or pointing to individual targets and providing both **range and bearing** information about the target without the need to pass directly over the top, thus eliminating the danger of accidental actuation which exists with many other detector systems. Since detection is no longer operator subjective, extensive training and practice is eliminated. Furthermore, due to both automated localization and standoff detection, (ability to point at the ordnance location without approaching it) time extensive grid searches are not required.

THIS CONCEPT APPEARS TO HAVE HIGH DUAL USE POTENTIAL. In addition to the obvious buried mine applications, other possible applications could be the location of buried ordnance including weapons caches, the location of steel pipes, oil drums and other buried steel containers, as well as armored cables. Because the magnetic signatures from long vertical targets such as stakes and wellheads differ significantly from long horizontal targets such as pipelines and both of these differ from the small discrete targets such as mines, selective software and circuitry can be developed to reject "junk" targets even though their magnetic signatures may be similar and coincidental with the targets of interest. The system has great potential both in administrative clearance, environmental cleanup, and civil engineering applications.

ACKNOWLEDGMENT

Funding for this effort was provided by Special Operations Research , Development & Acquisition Center (SORDAC) under the Special Operations Technology Development program, administered out of MacDill AFB, Tampa, Florida by Mr. Will Williams. The local Costal Systems Station project engineer was Ms Jody Wood, Code 10C. The authors wish to give special acknowledgement to Robert Leasko of the Coastal Systems Station for his assistance in providing facility support and his valuable assistance in the data collection phase of the program.

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A System for Performing Site Characterization for Test Ranges Containing Unexploded Ordnance

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ABSTRACT

Wright Laboratory has been tasked by the Naval Explosive Ordnance Technical Division, (NAVEODTECHDIV) to develop robotic platforms to perform characterization of areas set aside for ordnance testing. These areas require the identification and removal of the unexploded ordnance before they can be utilized for safe, productive use.

The characterization task is performed by autonomously sweeping a designated area with the Autonomous Tow Vehicle (ATV). The ATV tows the multiple sensor platform (MSP) containing a magnetometer array and a ground penetrating radar (GPR). The ATV provides the time and position stamp for sensor data. Analysts then review the post survey sensor data to determine ordnance position. The ATV makes use of several advanced technologies. A hybrid navigation and guidance system using an external Kalman filter delivers vehicle position based on information from a Differential Global Positioning System (DGPS) and an Inertial Navigation System (INS). Sophisticated path planning algorithms, and an intelligent software architecture provide a measure of autonomy. A data collection system controls the functions of the various sensors and manipulates the data stream to conform to an open ASCII data format and stores it to rugged removable hard disks for later analysis.

Keywords: autonomous vehicles, unexploded ordnance, magnetometers, ground penetrating radar, sensor fusion

1. THE UXO PROBLEM

The need for a characterization system is driven by the recent Base Realignment and Closure movement in the Department of Defense. Millions of acres of former test ranges, impact zones, and hazardous waste sites must be rendered safe before they are turned over for public use. That process is composed of three tasks; (1) characterization, the identification and location of ordnance and hazardous waste, (2) remediation, the removal of the ordnance and hazardous waste from the site, and (3) Waste Handling and Storage, the neutralization, render safe handling, or safe storage of ordnance and hazardous waste. Systems, such as the Subsurface Ordnance Characterization System (SOCS) are needed to quickly, safely, and accurately identify and locate subsurface ordnance and hazardous waste.

2. OBJECTIVES

The purpose of the SOCS development was to prove the concept of an autonomous, self propelled, data gathering system. The SOCS performs autonomous surveys of areas of interest, providing time and position stamps for sensor data samples. SOCS then stores this sensor data for later analysis. The product of this development effort will be a technology transfer package that will be used by private contractors to perform hazardous cleanup of public lands. The SOCS mission is to operate as a test platform and will be used to investigate the use of new and promising subsurface sensing devices. Coupling this platform with a standard test range provides a means of comparing the performance capabilities of each tested sensor directly.

2.1 SYSTEM DESCRIPTION

The characterization system is composed of the Autonomous Tow Vehicle (ATV), the Multiple Sensor Platform (MSP), and the Mobile Command Station (MCS). The ATV performs autonomous surveys of designated areas and provides the data collection system with time and position information. The MSP acts as a non-magnetic instrument carrier for testing sensor performance, and a platform for data collection. The MCS acts as the base station for control of the vehicle by the operator. It contains the operator interface, GPS base station, and the data analysis and display computers.

2.2 AUTONOMOUS TOW VEHICLE

The ATV consists of several integrated subsystems; the vehicle itself, the vehicle electronics subsystem, which provides for computer control of the vehicle, the navigation system, which provides time and position information, generates the path plan, and controls the vehicle during path execution, the communication system, which provides telemetry information for the GPS system, a video channel from the vehicle to the mobile command station, and a two way data link that transmits and receives status and command information from the operator, and finally, the data collection subsystem, which controls the sensors aboard the sensor platform, collects the sensor data during survey operations, and stores the data for later analysis.

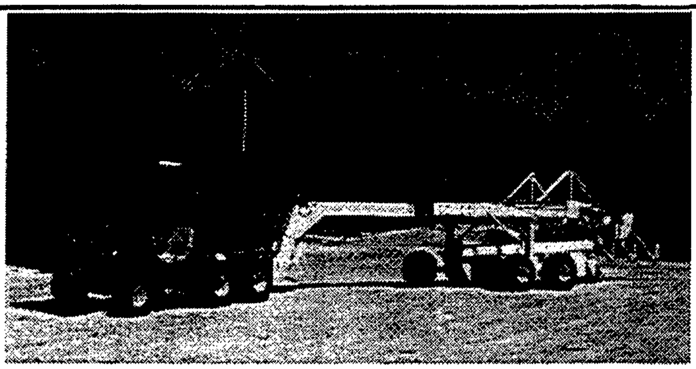

Figure 1 - SOCS

2.2.1 VEHICLE DESCRIPTION

The ATV chassis was based on the John Deere Gator. The vehicle has been modified to accommodate computer control and to reduce the overall magnetic signature. The Gator was chosen for a variety of reasons. One of the important factors in selecting the Gator was the ease with which it could be converted to computer control. Since the gearing was simple, it uses a centrifugal pulley system, no actuation was required to accommodate gear changes. Another factor was the rear cargo bed, which provided a convenient and simple platform for the integration of the necessary electronics, navigation, and communication equipment. Figure 1 shows its current configuration with the MSP.

In order to allow computer control, the vehicle's throttle, braking, and steering mechanisms have been slightly modified to accept actuating motors and absolute encoders. They were modified so that they could remain functional during manual operations. The actuation and information from the encoders from these mechanisms are then controlled by proportional, integrated, differential, PID, servo controllers which in turn takes direction from the guidance system.

2.2.2 NAVIGATION SYSTEM

The navigation system provides the means for the autonomous survey of a given area. The operator must provide information regarding the boundary of the area of interest and any obstacles contained within that area. Given this information the system will perform the following: (1) autonomously navigate the vehicle from its current position to the edge of the field to be surveyed; (2) plan an efficient path which targets 100% coverage of the field with a user specified overlap for each swath; (3) autonomously executes the planned path, collecting sensor data while avoiding collisions with expected or unexpected obstacles. These tasks are performed by three subsystems: the Path Planner, the Positioning System, and the Path Executioner.

2.2.3 PATH PLANNER

The area to be surveyed is assumed to contain regions where the vehicle is prohibited from operating. Buildings, trees, telephone poles, lakes, and other obstacles are represented as polygonal shapes and stored in an area map. A path planner is used to generate an efficient path from the starting position to a position at the beginning of the path for the area to be swept, from an area that has just been swept to another survey area, or back to the starting point[1].

2.2.3.1 Direct Path Planner

Direct Path Planning creates a direct path from the vehicle start position to a goal position. The first step in planning an efficient path is to expand all known obstacles in the local map so that the vehicle can be treated as a point. Figure 2 shows the polygon obstacles and their expansion. The amount of expansion is equal

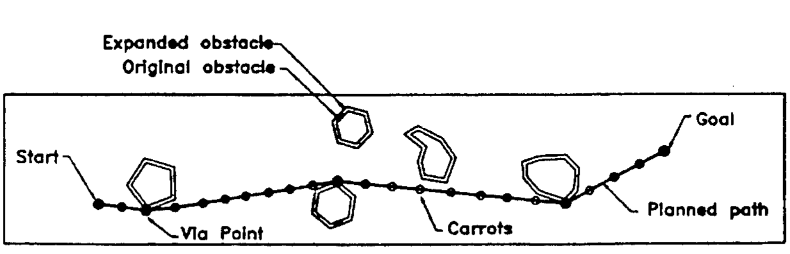

Figure 2 - Direct Path Planning

to the radius of a circle which circumscribes the vehicle. The A* search algorithm is then applied to determine the shortest path to the goal as follows: using the obstacle vertices which are visible from the current location, a cost is calculated using the sum of the distance to each vertices and the distance from there to the goal via a straight line. The lowest cost choice is selected as the first via point and the process is then repeated using all visible vertices from there. The process is complete when a straight line connects the current via point to the goal.

2.2.3.2 Survey Path Planner

Once the vehicle arrives at a goal position near the field to be swept, a second method of path planning is used to generate a field-sweep path.

A field is modeled by an N-sided polygon. Two adjacent vertices, A and B, are chosen and used to generate parallel rows across the field. The rows are separated by a user defined swath width, L, which represents the width of the detection system, plus a desired overlap. Point A is the start position for field sweeping. Point B is required to be the point next to A such that motion from A to B is clockwise motion around the boundary. The line segment AB corresponds to row #1.

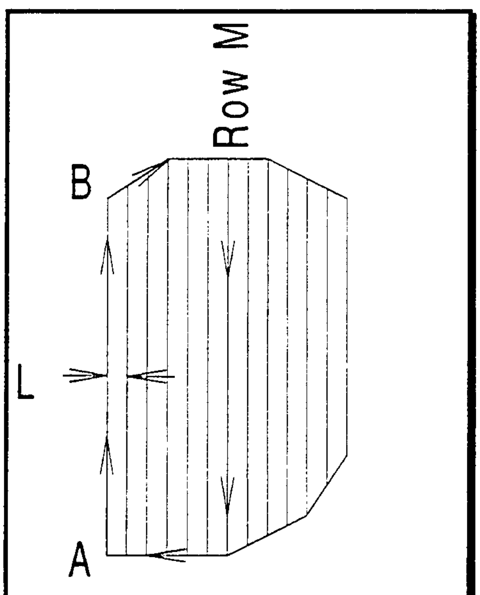

Figure 3 - Survey Path Planning

The endpoints of the rows are used to define the path to be followed, where K is the number of rows to be swept for the field. Each row is checked for intersection with the obstacles loaded into the database. Wherever an intersection is encountered, an alternate route around each side of the obstacle is examined. The shortest detour is incorporated into the total field sweep path.

The current sweep pattern used for the survey vehicle is the "Half Field Method," see Figure 3. Row #1 is swept followed by the middle row M, where M=K/2. Next, row #2 is swept followed by the middle row (M+1). This pattern is continued until the entire field has been swept. This method does not require a row be swept more than once except when K is odd. In such cases, row M is swept twice.

2.2.4 POSITIONING SYSTEM

To successfully navigate along a pre-planned path, the ATV must have some means of accurately and consistently determining its position and orientation. This problem is being addressed by the application of an inertial navigation system, INS, integrated with a differential global positioning system, GPS.

The ATV uses the Modular Azimuth Position System, MAPS for inertial navigation. The MAPS is a completely self contained, strapped down, laser gyro system. Given an initial position, the MAPS makes use of its three ring laser gyros and three accelerometers to determine relative position, angular orientation, and velocities. Position and orientation data from the MAPS are made available at a rate of 12.0 Hz. The MAPS makes use of velocity updates to damp velocity errors that cause drift in the position accuracy over time.

The GPS system implemented uses P and C code RF signals, which are transmitted from orbiting satellites, to determine position and velocity data at a rate of 0.5 Hz. A single GPS unit is subject to a number of errors outside the control of the receiving unit. The military introduces two forms of random errors into the signal known as selective availability and anti-spoofing. Under these conditions, the GPS only delivers absolute position to within 80.0 meters. To increase the system's accuracy, a method known as differential GPS is being applied: A GPS receiver is placed at a known pre-surveyed location, the base station. A second remote GPS receiver is placed on the moving vehicle. Using prior knowledge of its position, the base station receiver can determine the systematic or bias errors from the incoming signal. The corrections are then transmitted to the remote vehicle, where they are then used to reduce errors. Position data have been found to be accurate in the range of 2-10 centimeters 85% of the time using this method.

The integration of the GPS with the MAPS has greatly increased the overall system performance. The two systems complement each other well in that the MAPS provides continuous data at high rates while the GPS

system is not subject to drift. The external software Kalman filter uses models of the navigation instruments used, and an error history of these same instruments to predict current vehicle position. This system provides a robust means for acquiring position during intermittent dropouts or spurious instrument errors.

2.2.5 PATH EXECUTIONER

The path executioner continuously generates a recommended steering angle and vehicle velocity that keeps the survey vehicle on the pre-planned path until the goal is reached. The path is used to obtain sub-goals at 3.0 meter intervals. Around corners, sub-goals are placed on the interior of the path to ensure a smooth transition between segments. PID control is used to steer the vehicle directly towards the current sub-goal. The desired vehicle velocity is a linear function of the distance to the next turn and the sharpness of that turn.

2.2.6 DATA COLLECTION SYSTEM

The data collection system uses several file systems to store configuration, real time, and target information. The Interplatform Data Set, IDS, contains all of the configuration and environmental data and describes: sensor descriptions and geometric locations, weather, terrain, time, date, and location of the test area. The Semi-Raw Data Set, SRD, contains a header describing a sensor. The data field contains a time record and an associated sensor sample. A separate SRD is then generated for each sensor type and is keyed to the IDS by the sensor description and the time and date. An additional SRD is generated by the navigation system that contains records for time and position. This file is then used during post processing to determine position for the sensor data for any given time. The Standard Data Set, STD, is generated following post processing and an analysis of the SRD file. The STD is then composed of target information: position, orientation, and an estimate of the ordnance type and class. These file formats are defined and described in The Simultaneous Data Collection and Processing System Interplatform Data Set[2].

Figure 4 shows a functional diagram of the Data Collection System and its interface with the ATV Navigation System. The figure shows that the Data Collection System both controls the functioning of the sensors as well as directing the data stream from the sensors. In addition to directing and manipulating the data stream, the Data Collection System acquires time and position from the ATV Navigation System. The details of the interaction between the different subsystems may be found in the SOCS Interface Design Document[3].

2.3 MULTIPLE SENSOR PLATFORM

The Multiple Sensor Platform was developed to provide a structure for an array of cesium magnetometers and a hanger for a Ground Penetrating Radar, GPR. The platform is shown in Figure 1. The GPR is suspended below the platform frame via a pinned hanger. That hanger structure contains an encoder which measures the relative angular displacement from the platform frame which is also written to an SRD file for GPR position resolution. The magnetometers are hung from the rear of the platform via an articulated beam. The beam can be secured in various pitch attitudes with respect to the platform. In addition the magnetometer sensor head clinching mechanism secure the sensor with variations in roll.

3. TEST RESULTS

System testing was conducted on the SOCS during April and June of 1995. These tests showed the general functioning of the autonomous operations, the ability to reliably collect valid sensor data, and verified the positional accuracy of the vehicle. For all tests, the vehicle traveled approximately 3-3.5 mph, which is normal operating speed.

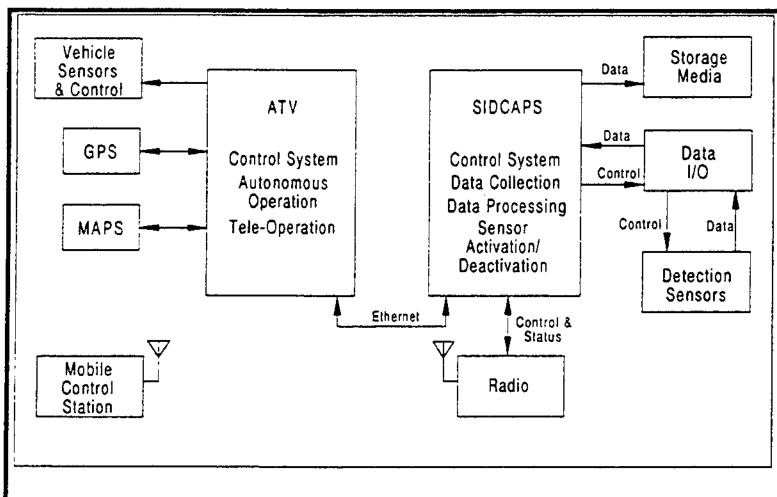

Figure 4- SOCS Functional Diagram

A series of tests were performed to determine the ability of the vehicle to follow a planned direct path and a survey path. Figure 5 shows a typical direct path result. This path was 533 feet. For 8 test runs, the average position error was 2.2 feet with a final orientation error of 1.2 degrees. This figure shows the planned path versus the path traversed. The data for the actual path

followed was taken from a post processed log of Differential GPS data that has demonstrated accuracy's of 2 centimeters for 80% collection time.

Figure 6 shows a typical survey path result. The figure shows the starting and ending positions for the area surveyed. This path covered an area of 0.6 acres with 99.8% coverage for a swath width of 8 feet. The total path length was 6470 feet and yielded a coverage rate of approximately 1.5 acres per hour.

The SOCS was taken to Jefferson Proving Grounds (JPG) in August of 1995 to take part in the NAVEODTECHDIV's JPG Phase II demonstration. The intention of the demonstration was to show the current state of the art in UXO characterization systems available throughout the government and industry. Inert ordnance were placed throughout the test site and their positions and orientations were recorded. The test site then became a truth table for all demonstrators who brought their systems to JPG. The SOCS surveyed approximately 12 acres over a period of 5 days. The complete results of those tests will be published by NAVEODTECHDIV.

Figure 7 shows the vehicle path for a typical field at JPG. The diamonds indicate the user selected vertices defining the field to be surveyed. Note the two holes in the survey, these were obstacles recorded earlier and input into the local map. The obstacles in this case were small trees. Note also that the lines are not continuous at the ends of the survey runs. SOCS stops data collection at the end of each run to reduce the amount of redundant data collected. Figure 8 shows the swath coverage for the same field at JPG. Although the coverage was 97%, the holes created by the obstacles were counted in that coverage. It is important to record these missed areas so that they may be revisited and investigated.

4. SUMMARY

The SOCS system was developed as a test platform to measure the effectiveness of various sensors to determine the orientation and position of subsurface ordnance. It must be noted that the objectives of this test were not to verify ordnance locations. The objectives were to determine whether SOCS could perform autonomous data collection. That objective was successful. To reach the objective of ordnance verification, the operational characteristics of both the magnetometers and the GPR must be determined. Once this has been accomplished, operational testing, with the intent of characterizing its detection capability, of SOCS may be performed

The SOCS was developed for autonomous operations because of the difficulty of accurately controlling the position and orientation of a remote vehicle, and because of the inherently hazardous conditions in which it must operate. The ATV provides a time and position stamp for all sensor data collected aboard the Multi-Sensor Platform. The integration of vehicle control and sensor data collection makes the SOCS system unique. Although the SOCS system cannot be used in all terrain, it does provide a unique capability for the vast majority of test range and impact zone sites..

5. REFERENCES

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3. WINTEC Inc., "SOCS Interface Design Document," USAF Contract #F08637-94-C6042, June 1995.

Results - 1 June Evaluation

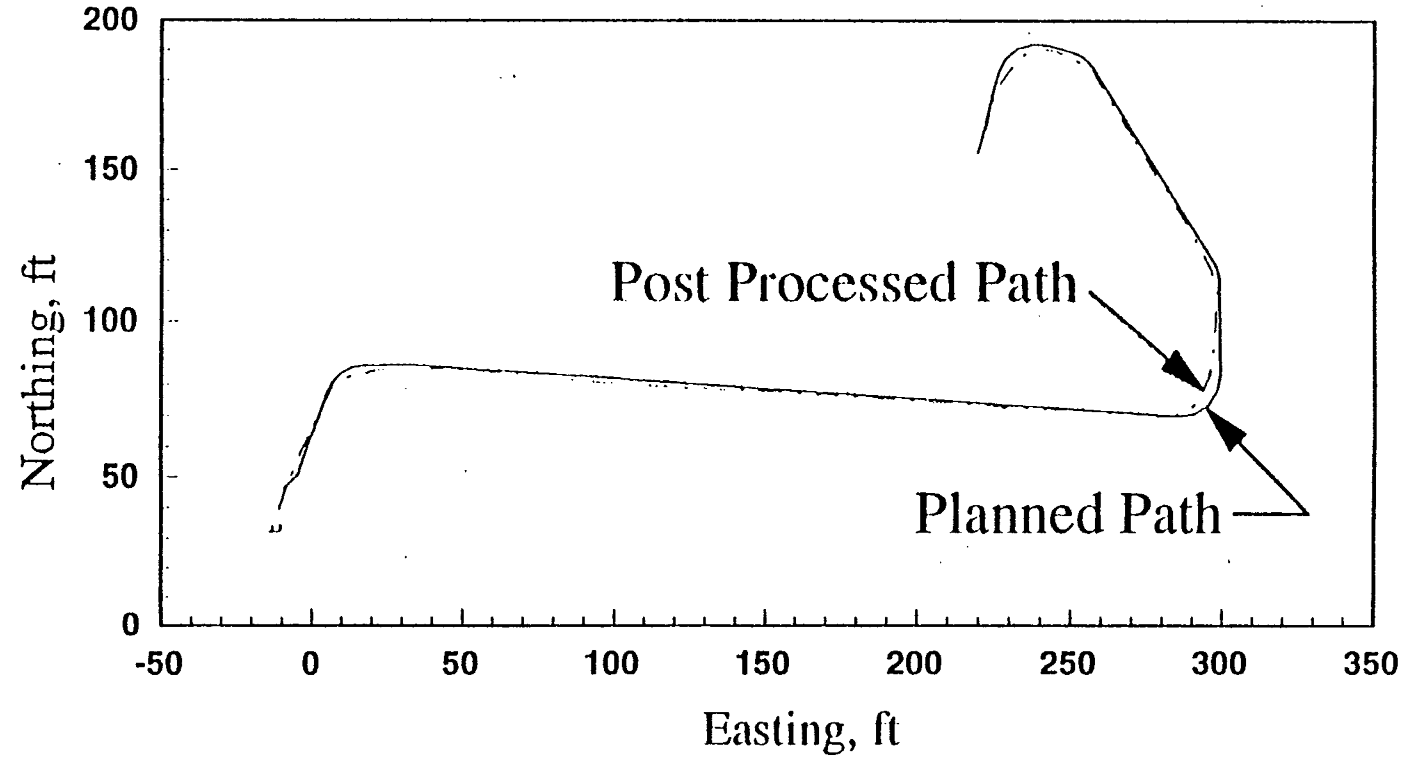

Figure 5
Direct Path Results

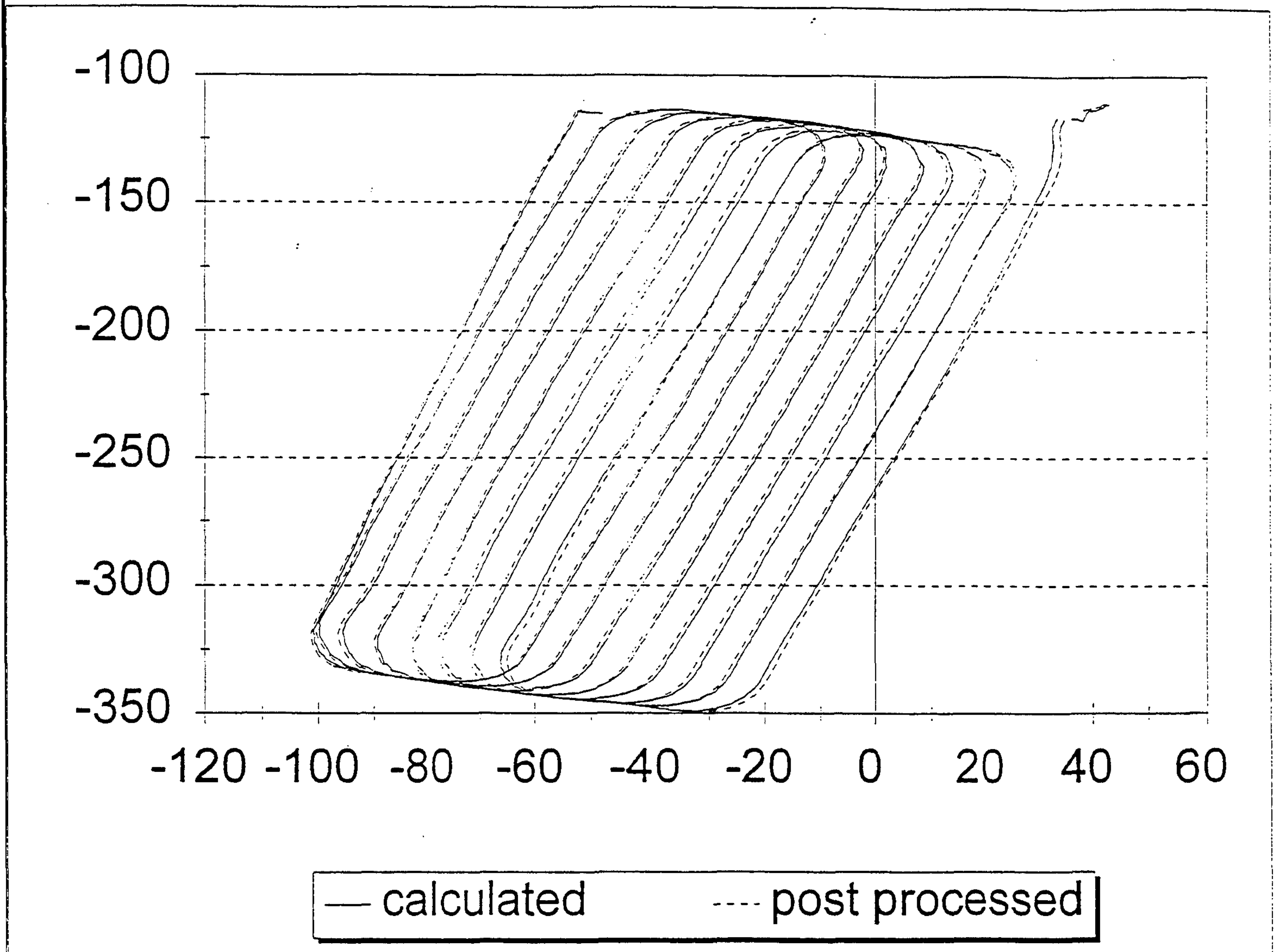

Figure 6
Survey Path Results

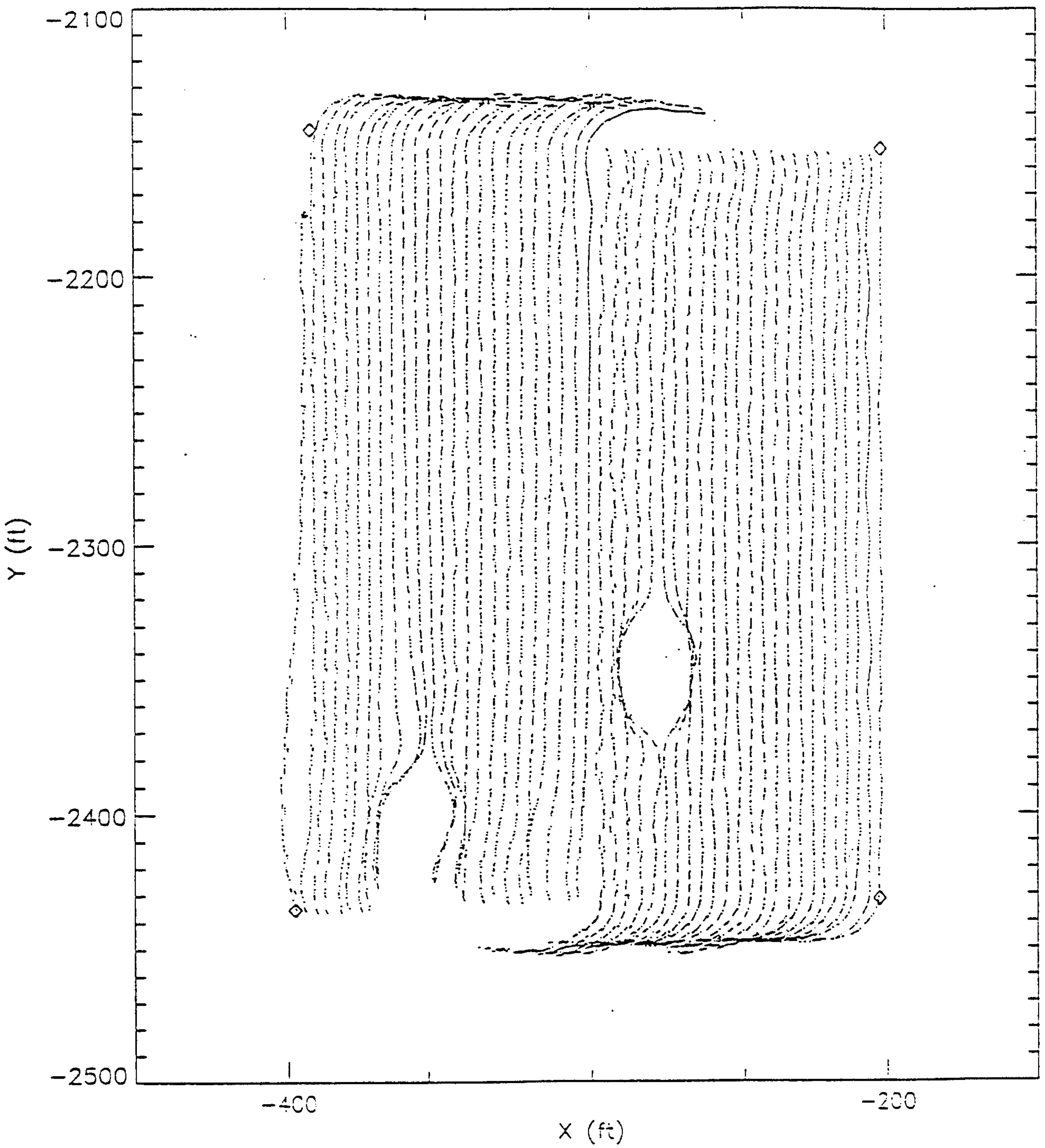

Figure 7
Survey of JPG Demonstration Field

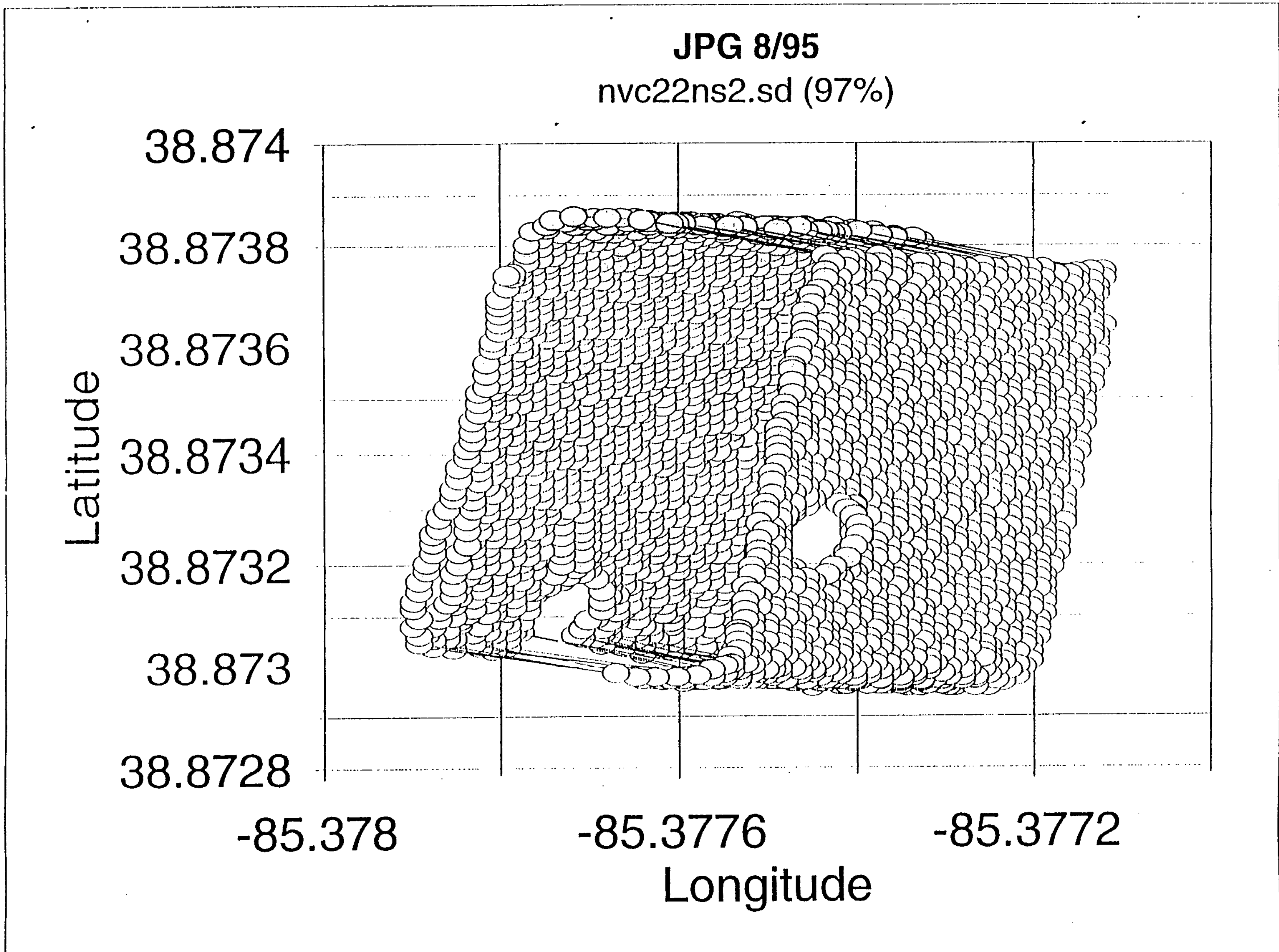

Figure 8
Swath Coverage for JPG Demonstration Field

MINE DETECTION WITH MODERN DAY METAL DETECTORS

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INTRODUCTION

With the end of the cold war, the threat of nuclear conflict has been substantially reduced. Countries around the world view this situation with both celebration and opportunity. One negative result has been an increase in regional conflicts over national and political sovereignty.

The world has seen a dramatic increase in the use of landmine warfare in many regions. Today, there is an estimated 100+ million mines which will require detection and disposal work. One reason for this increase is due to the relatively inexpensive cost of mine deployment with relationship to a highly effective strategic effect.

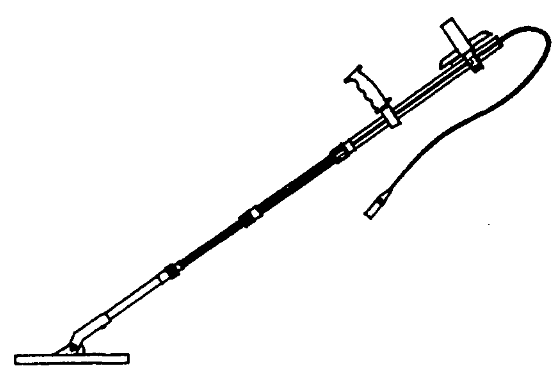
Responsible Governments are now challenged with the remediation of these mine saturated areas. In war zones this problem is compounded with the combined nuisance of OEW in the same fields.

There are a large variety of mines contaminating the planet and many contain only a very small amount of detectable metallic content. Today, manufacturers must design and produce highly reliable instruments for the detection of these mines and to insure the safety of EOD personnel. It is currently thought that approx. 99% of the placed mines contain some metal content. Therefore, modern day mine detectors with reliable technologies are very viable in meeting this remediation challenge.

APPLICATION

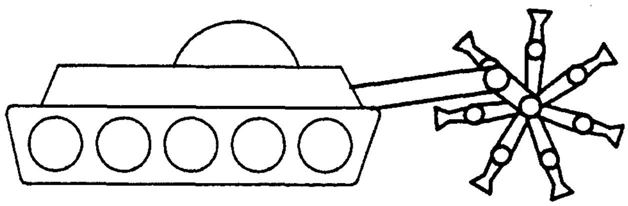
To remediate and render safe an area which is contaminated with mines, ammunition, and OEW (or the combination of these hazards), the surface must first be cleared from these explosives. This can be accomplished by two basic methods:

1. MINES: First, mines must be detected with a hand-held mine detector and immediately removed / deactivated. This work can be very fatiguing for the EOD operator and can only be done manually.



Mine clearance

So-called efficiency methods which use heavy machinery or explosives are not recommended because it cannot be ensured 100% that the mines will be destroyed. Further, a lot of metal fragments will be scattered over the area rendering it impossible to perform a repeat survey scan.

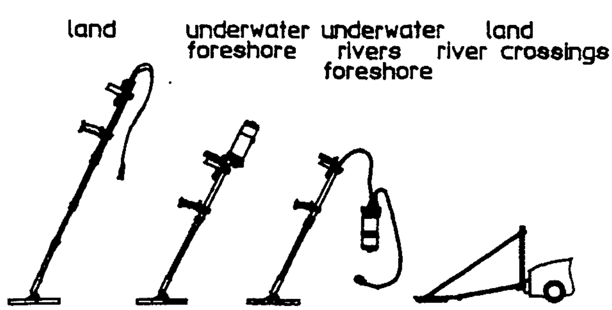


Mine breaching

2. OEW: For the detection of UXO and Explosive Waste (mines excluded), both metal detectors and magnetometers may be used together to clear surface and sub-surface targets. Advanced detection systems are available which will produce target lists and maps to assist with the removal process of these items.

DETECTOR SELECTION

For both of the above noted methods a variety of detectors are available on the market. However, only a select few models will meet the safety and detection needs for mine detection requirements.



Commercial advertisement from some companies claim detection statistics which are often only with reference to ideal level ground conditions (i.e. desert sands, roadways). Understandably, under these conditions there are several mine detectors which will produce acceptable mine detection results with little differences from one detector model to another. Unfortunately, the "real world" conditions can be overlooked by novice customers during the detector selection process.

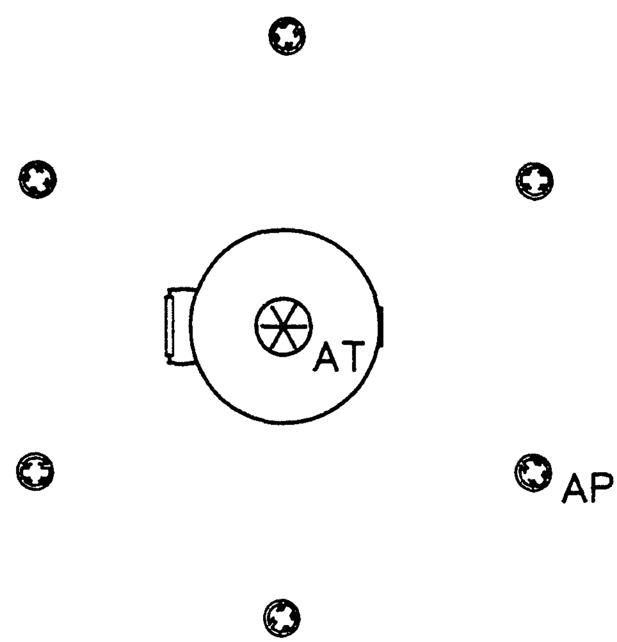
GROUND / SHALLOW WATER CONDITIONS

The following field conditions are typical considerations which are commonly encountered in mined areas:

- Searching on very uneven surfaces.
- Searching in brush, high grass, and along narrow pathways.
- Searching along embankments and cliffsides.
- Searching in muddy soil, magnetite soil, saltwater mixed soils.
- Extreme weather conditions.

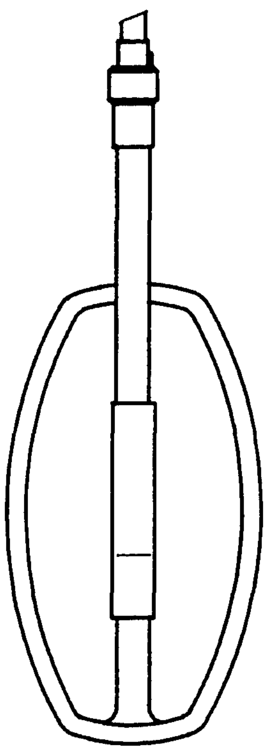
This means a metal detector (mine detector), should work to it's optimum level in all conditions to assure reliable and safe operation.

Moreover, the detection sensitivity must be very high level to detect both small metal items such as firing pins in plastic mines and larger metal targets at a greater distance below the surface. In wartime scenarios small AP mines may be placed in close proximity to larger AT mines. The detector should be able to discriminate these different targets to avoid detonation.



These requirements can only be fulfilled by a "modern day" mine detector with highly sophisticated electronics combined with an optimum physical working design. For this purpose, Vallon GmbH produces their model ML1620B along with several variations for special user requirements.

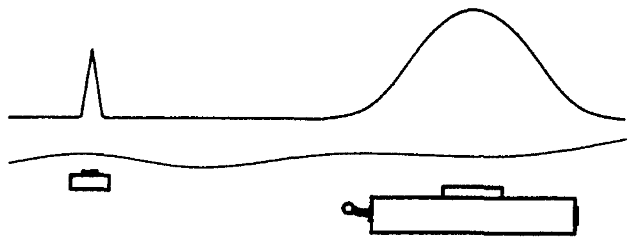
Specific details from Vallon such as their patented "Oval" search head design is highly suitable for searching under brush and near rocks, etc., and allowing the operator to maintain a necessary minimum distance between the search head and the target. Additionally, this open frame design allows a clear view of the search area for precise coverage. The lightweight design reduces operator fatigue.



TARGET RESPONSE

As the complete information of a target detection is received from the search head, a very clear and unmistakable audio alarm signal is produced by the ML1620B detector. This signal not only alerts the operator to the found target but helps pinpoint the center of the target with high accuracy.

This means that the produced audio signal must be proportional in volume and frequency to the size of the metal target and to the detection distance; the signal must not contain any other information. Interference from metal debris or other targets outside the detected target must be discriminated out or the operator will fatigue quickly and reduce the safety level of the operation.

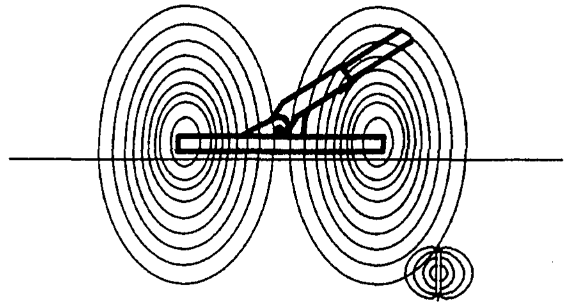


MEASURING PRINCIPLES

As already mentioned, it is estimated that approx. 99% of the ammunition and mines contain some metal content. The Vallon company has the advantage of 30 years experience in the industrial sector in the development of measuring instruments which is applied directly towards the effort of mine detection.

In principle, applied metal detection means testing the soil on specific conductivity or spots of permeability. Whereby a metallic part reacts like a linear electronic filter. This is why the metal detector consists of one or more induction coils which are controlled by an electronics unit.

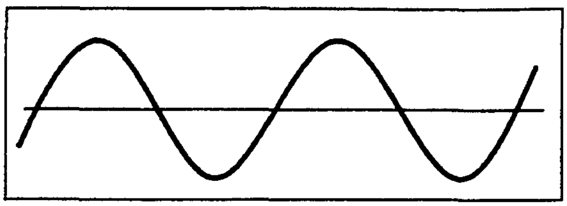
Each metal detector emits an electromagnetic field which will be influenced proportionally by the amount of electrical and magnetic conductivity within it's slope. However, not only mines or other man-made objects belong to the electromagnetic influences of the detector. Mineralized soils, water with chemical contamination, and salt water conditions produce false effects or reduce the detector's sensitivity level without the operator's awareness.



Therefore, it is absolutely necessary that the metal detector uses a measuring principle which does not produce false signal indications under the full variety of ambient conditions (the detector must also adapt instantaneously to changing ground conditions without the need for operator adjustments). For this purpose, either a single coil design (which serves as both transmitter and receiver), or a multi coil design (one transmitter coil and one or more receiver coils), may be selected.

These coils can be activated by an electronics source of either a continuous current "sinewave" or by "pulse" induction.

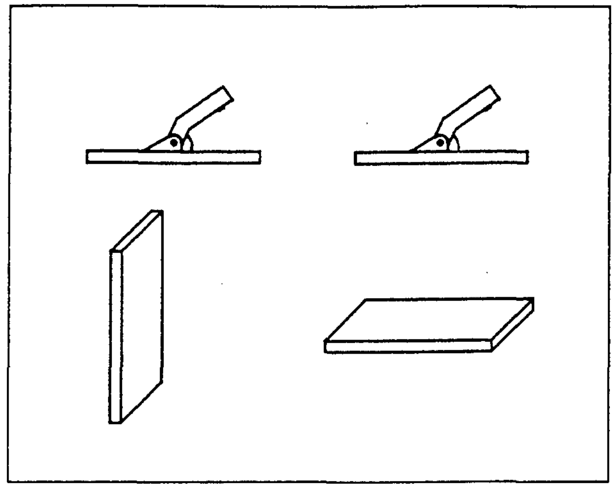
A. SINEWAVE (continuous wave), detectors emit a permanent electromagnetic field which will be influenced by magnetic or electrically conductive materials in amplitude, phase, and / or frequency.



The intensity of this influence will vary depending on the frequency (RF) applied as each type of metal must relate to an optimum frequency. This is why in the application of non-destructive testing (used by some manufacturers in the industrial sector for test documentation), the detector's operating frequency will be chosen depending on the material to be tested. Alternatively, an entire frequency range will be passed in order to obtain as much information as possible for a detector's true range.

However, experiences from this testing range cannot be directly or fully transferred to real field applications. During laboratory measurements the preparation consists of an ideal relationship between metal test samples and the detector's search coils.

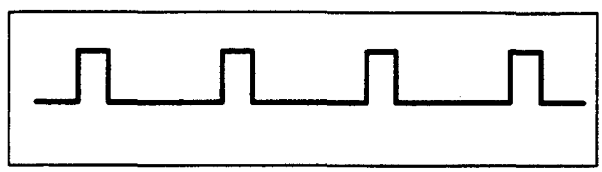
In the case of small metal targets (i.e. plastic AP mines) the metal detectors are highly and strongly influenced by the conductivity and permeability on the ground with a much smaller influence from the metal object. The metallic content, shape, and orientation of the small target will also influence the measuring results.



Only via electronic manipulations the false alarm signals from the various soil conditions are reduced to lower levels.

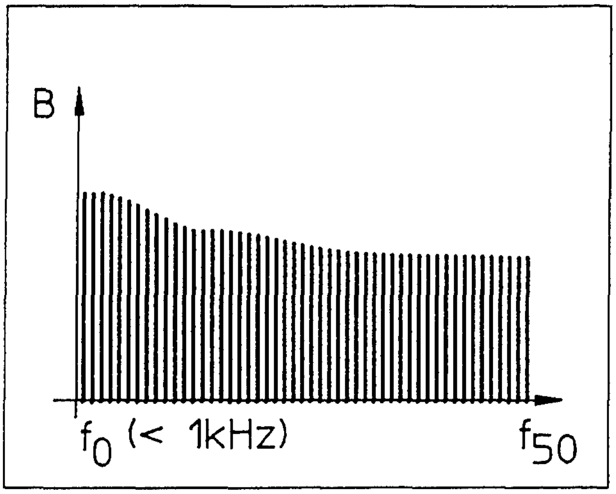
One past known hallmark of the continuous wave detector is the ability to obtain a high sensitivity detection level in soils with low electrical of magnetic conductivity. To avoid interference by ground effects in more conductive soils some manufacturers will use different coils within the same detector search head. This principle will work but is only partially effective on a very flat ground surface where the interference of the metal object is homogenous to both measuring coils.

B. PULSE INDUCTION detectors are useable in both ground searching and underwater searching applications. The ambient field conditions do not directly effect the detector's sensitivity settings. Therefore, a direct and reliable evaluation of the detector's signal is possible.

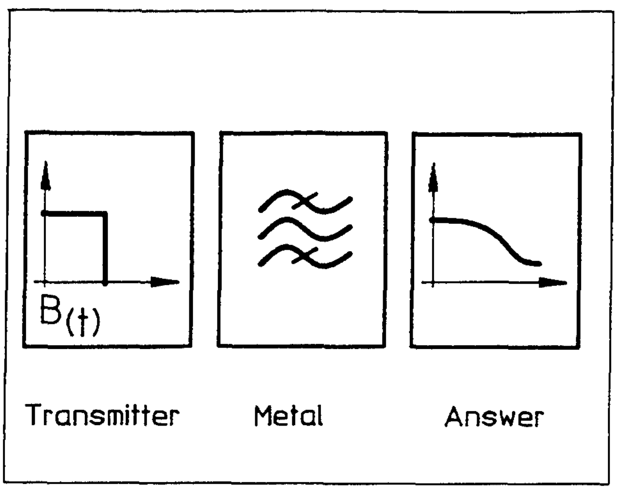


Typically the pulse detector does not achieve the same high detection sensitivity level as the continuous wave detectors. However, Vallon R & D has developed an "advanced pulse" detector which can detect equal metal targets at the same high sensitivity levels as the continuous wave detectors (without the concerns of conductive soil interference problems).

The electronically induced current impulsed through the detector coil produces an electromagnetic field which contains a high quantity of frequency points.



When this information is evaluated it corresponds with the pulse detector's many working frequencies. This allows for the use of optimum information during the process of target discrimination from ground influences.



Here, the differences in ground effect interference and a metal object is far more evident with the use of a single coil pulse detector than from multi coil arrangements. A precise signal is produces for the operator without complicated discrimination procedures.

Use of the pulse detector provides a measuring technique where digital application enhancements can be applied. Standard features include stability in all soil conditions and in all operating temperature conditions. The functions are continuously monitored and checked for 100 % reliability during use. The detectors can operate in a synchronous fashion allowing for side-by-side sweeping operations.

UNDERWATER CONDITIONS

Vallon has designed a metal detector for both underwater and land use; model MW1630 (MK29 MOD 0). As with the land version model ML1620B, this detector employs Vallon's "advanced pulse" technology.

Salt water or chemically contaminated water will not influence any operating functions. This principle also applies when using the detectors during changing soil conductivity conditions. The operator simply selects a sweeping mode and sets the desired sensitivity level. This allows for complete concentration during the searching operation. No adjustments are required making the safety level of the operation optimum for metal detector requirements (the detectors automatically adjust to changing ambient / pressure conditions without loss of sensitivity).

CONCLUSION

Mine detection in itself can be a high-risk occupation. Apart from proper training, it is essential to have mine detectors that are electronically and physically superior for the task at hand as the highest issues are safety and confidence in detection.

The proper design and understanding of mine detectors is a specialized field from which a limited number of manufacturers possess the experience and proper knowledge to fabricate top line equipment. Users of this equipment should understand the parameters of these instruments and the essential need for high quality products.

UXO Characterization Using a Remotely Controlled Vehicle

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ABSTRACT

A remote characterization system (RCS) is being used at the Aberdeen Proving Ground (APG), Maryland, Edgewood Area, a National Priorities List site, to conduct geophysical surveys at Carroll Island. The surveys are designed to verify the boundaries of potential burial sites, disposal pits, and munition impact areas as part of a Remedial Investigation being conducted under the Comprehensive Environmental Response, Compensation, and Liability Act. APG is located within the Upper Chesapeake Bay. Between 1941 and 1969, portions of Carroll Island were used as a Chemical Warfare Materials (CWM) test site and as an impact area for munitions testing.

The RCS is a prototype and consists of four components: a remotely controlled Low-Signature Vehicle (LSV), a base station, navigation/communication subsystem, and sensors. The LSV was designed with a minimum of metal to reduce any electromagnetic signature that might interfere with sensor operation. The base station houses the vehicle controls and monitors. Sensor readings flow continuously from the LSV to the base station. A differential Global Positioning System (GPS) is used to track the vehicle in real time with an accuracy of less than 1 meter. GPS data can be processed to achieve decimeter accuracy.

Approximately 190 acres have been surveyed at four areas at Carroll Island using dual total-field magnetometers, an electromagnetic sensor (EM61), and ground-penetrating radar (GPR). The vehicle can survey approximately 2 acres/hr. Preliminary evaluation of the data indicates that the magnetometers are the most effective tools used at this site. The EM61 is also proving highly successful. GPR data have not been fully evaluated, but preliminary results suggest that clay-rich conditions at the site are limiting the depth of the radar penetration to a few feet. Hundreds of anomalies have been detected. Most anomalies can be attributed to man-made features associated with the sites. However, several large anomalies cannot be tied to known features or known past practices. Overall, RCS technology has been proven very effective at Carroll

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* Operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO 1830.

** Worked performed by CACI·ASG, Inc. under general order contract number 17K-MD310C with Lockheed Martin Energy Systems, Inc.

Island. It is more efficient than a traditional geophysical survey because all the sensors operate simultaneously. The greatest benefit of the RCS to APG is that as much data as needed can be collected with complete worker safety in areas with potential for CWM or other unexploded ordnance.

INTRODUCTION

The Remote Characterization System (RCS) uses a small, remotely controlled vehicle as a platform for a variety of nonintrusive sensors that can detect and map unexploded ordnance (UXO) and other types of buried waste material. The existing prototype was constructed in the 1991–1993 period as a collaborative effort involving the U.S. Department of Energy's Pacific Northwest National Laboratory, Idaho National Engineering Laboratory, Oak Ridge National Laboratory, Sandia National Laboratory, and Lawrence Livermore National Laboratory. The development effort was jointly supported by the Department of Energy's Office of Technology Development and the U.S. Army Environmental Center.

The RCS is a remotely controlled system that can perform large-scale site characterization surveys using telerobotics and thereby minimize the risk to personnel while offering a high level of efficiency and cost-effectiveness. It takes advantage of the efficiency of a vehicle-based survey system while minimizing the problems of limited maneuverability and the degradation of sensor performance as a result of interactions with the vehicle. The ability to operate the survey vehicle and its on-board sensors by remote control is a key to safe survey operations at sites that are hazardous for human operators either on foot or on board a survey vehicle.

The prototype system recently was used to perform geophysical surveys at the Aberdeen Proving Ground (APG) Edgewood Area, a National Priorities List site. The surveys were performed at several locations on Carroll Island and covered a total of approximately 190 acres. The survey was designed to verify the boundaries of potential burial sites, disposal pits, and munition impact areas as part of a Remedial Investigation being conducted under the Comprehensive Environmental Response, Compensation, and Liability Act. The site, survey, field operations, and results of the surveys are described below.

SITE DESCRIPTION

APG is located in Harford and Baltimore counties, Maryland, near the head of the Chesapeake Bay. The installation is approximately 79,000 acres in size, of which approximately 30,000 acres is land divided between the Aberdeen and Edgewood areas (Dames & Moore 1995). Carroll Island, where the RCS was used, is part of the Edgewood Area (Figure 1).

The principal mission of APG is testing and evaluating conventional and Chemical Warfare Materials (CWM). Testing activity began at Carroll Island as early as the 1940s; and in the early 1950s, most of the testing of lethal chemical agents was moved from other areas to Carroll Island and another adjacent area. All CWM testing was discontinued in 1962.

Carroll Island is approximately 855 acres in size. It is classified as 20% upland and 80% wetlands; approximately 40% is tidal marsh. The highest point is about 13 ft above mean sea level. The rolling terrain is poorly drained, and temporary ponds and pools form seasonally inundated wetlands. The estuaries surrounding Carroll Island are used for recreational purposes such as fishing and boating (Dames & Moore 1994).

Many sites on Carroll Island were surveyed by the RCS; the main areas are Test Grid 1, Test Grid 2/Lower Island Disposal Site, the CS Test Area, the VX Test Area, and the HD Test Areas. The Test Grid 1 site was used for CWM testing from the late 1940s to 1969. During the mid to late 1940s, part of the area reportedly was used as an impact area. In the late 1940s the area was used for flamethrower testing. A test grid consisting of sampling apparatus located in concentric circles 20, 30, 40, 50, 75, 100, 150, and 200 yards from a central testing area was constructed in the early 1950s and improved in the 1963. The sampling system included ground-level samplers and an underground sampling system (Nemeth 1989). There were also underground drainage and control systems. A 60-ft drop tower is located neat the center of the grid. The grid circles are no longer visible on the ground.

Test Grid 2 is similar to Test Grid 1 except the grid was a half-circle and it had no underground drainage, sampling, or control systems. Use of the area began in the mid-1940s as an impact area. All types of CWM were tested at Test Grid 2 until 1969. The Lower Island Disposal Area consisted of approximately 10 burial pits and a marsh dump site. All but one pit was covered with soil when filled. The contents of the one open pit was removed in 1993 as part of an interim remedial action. There is little surface evidence of the disposal pits.

The CS Test Area was used for ground contamination studies involving CS (an irritant). Very little historic information is available on this site. The HD Areas were

used for ground contamination studies. Approximately 1,500 to 2,00 pounds of HD were reportedly released using land mines (Nemeth, 1989). HD is also called mustard and is a blistering agent. The VX Test Area consisted of four concrete pads used for CWM testing. The pads were used for contamination/decontamination studies. It is estimated that approximately 600 pounds of VX, a potentially lethal agent, were released during testing (Nemeth, 1989).

SYSTEM OVERVIEW

The main components of the RCS are (1) a small, self-propelled, remotely controlled survey vehicle; (2) a truck-mounted control station (or base station) that normally is located outside the survey area; (3) subsystems for telemetry and navigation; and (4) a set of sensors for target detection.

Survey Vehicle

The materials and components used in the construction of the survey vehicle were largely nonmetallic to minimize the effects of the vehicle on the response of the sensors. The resulting prototype Low-Signature Vehicle (LSV) contains approximately 130 lb of metal, but this material is distributed so that it has only a small effect on the on-board geophysical sensors. The amount of magnetic material (steel) on the vehicle was minimized, and unavoidable steel components were located as far from the magnetometers as possible.

The vehicle was designed to turn in place to enable it to maneuver around common obstacles such as bushes, trees, holes, rocks, and miscellaneous debris (wire, cable, 55-gal drums, concrete blocks, etc.) In addition, it was planned that all sensors and other vehicle components would be contained within the perimeter of the vehicle as defined by its wheels and bumpers. In particular, the large size of a GPR antenna and the necessity of coupling it to the ground virtually dictated that the vehicle be designed around it. Thus, as illustrated in Figure 2, the front part of the chassis is an open structure that permits the GPR antenna to be suspended between the front wheels. As shown in Figure 2, the requirement that all sensors be contained within the perimeter of the vehicle was relaxed for the APG survey because the areas to be surveyed were mainly open fields that contained only a small number of obstacles.

The LSV is based on a six-wheeled design with modified skid steering. It is approximately 7 ft long and 5 ft wide and weighs approximately 800 lb, which includes a payload of approximately 150 lb. Its major components include the chassis, engine, drive train, and an electrical power generator. They also include an on-board digital controller and peripheral devices to monitor vehicle status and to provide low-level control inputs to the vehicle.

The chassis is articulated to minimize the vertical movement of the instrument platform in response to the roughness of the ground surface. It consists of two main sections that form the rear third of the forward two-thirds of the vehicle, respectively. A pivot located on the vehicle's longitudinal axis allows the front and rear sections of the chassis to rotate relative to each other. Additional articulation is provided at the front end of the chassis. Two wheels on each side of the front section of the vehicle are mounted at the ends of a horizontal arm that is connected by a bearing to the end of the inverted U-shaped member that straddles the front part of the chassis. Each arm is free to pivot about a transverse axis located at the center of the arm.

A 20-hp, gasoline-powered, 2-cylinder engine is mounted on the rear section of the chassis. A 12-V, 50-amp alternator mounted on the engine provides electrical power for the sensors, control modules, and other electronic devices on the vehicle. A hydraulic pump, electronically controlled hydraulic valves, and four hydraulic motors provide power at the front and rear wheels.

The LSV has been designed to climb and traverse 35° slopes, to have a ground clearance of 8 in. (except for the GPR antenna), and to operate at speeds up to 4 ft/sec. At Carroll Island survey sites, the LSV was routinely operated in marshy ground with standing water up to 10 in. deep.

Base Station

The LSV is controlled by an operator located in the base station (Figure 3). Telemetered video signals give the operator the visual information needed to drive the vehicle across the survey area and avoid any obstacles present. Digital commands for vehicle and instrument control are transmitted to the vehicle. Data produced by the on-board sensors are transmitted from the vehicle to the base station, where they are recorded, processed, and displayed.

The central component of the base station is a control chair with vehicle joystick controls and a keyboard/trackball interface for command inputs to the graphics-based operator interface. The remote video images and a graphical interface to the control computer are presented on video displays located in front of the

operator. A secondary graphical data display station is provided to allow a geophysicist or observer to examine real-time data.

Telemetry and Navigation

A digital, radio frequency, command/data link provides ethernet communications between the vehicle and the base station. Signals transmitted to the LSV control the direction and speed of the vehicle, the orientation of the video cameras, and the setup and operation of the on-board sensors. Vehicle status information and sensor output data are transmitted from the LSV to the base station. This approach permits data to be transmitted at 25 kbytes/sec, a rate sufficient to handle the 17-kbytes/sec output of the GPR sensor together with the output of all the other sensors. Two separate analog RF channels handle video transmissions.

Vehicle/sensor tracking is provided by a differential kinematic implementation of the satellite-based Global Positioning System (GPS). Two NovAtel (Calgary, Alberta, Canada) GPSCard Model 951R receiver modules are used. The first, mounted on the LSV, computes its location and transmits that information to the base station via the telemetry link. The second, mounted on the base station truck, is fixed in position for a given survey and provides error-correction information that is transmitted to the LSV's GPS receiver. Coordinates accurate to ±50 cm (typically) are calculated in real time at a rate of 5 measurements/sec. Coordinates accurate to ±15 cm (typically) are obtained by postprocessing the recorded GPS data.

Sensors

The following sensing instruments were mounted on the LSV during the APG survey:

- two cesium vapor magnetometers (Model G822A, EG&G Geometrics, Sunnyvale, California),
- ground-penetrating radar (Model SIR 7, Geophysical Survey Systems, Inc., North Salem, New Hampshire), and
- metal detector (modified Model EM61, Geonics Ltd., Mississauga, Ontario, Canada).

CARROLL ISLAND SURVEY

The objective of the geophysical surveys performed at the Carroll Island sites was to identify disposal pits and UXO impact areas. Because it was not considered necessary to detect every small object, the spacing of the LSV traverse lines was set at 10 ft. With a 5-ft lateral spacing of the dual magnetometers on the LSV, the resulting magnetic line spacing was approximately 5 ft. Magnetic and metal detector measurements were made at intervals of approximately 1.5 ft in the along-track direction. The corresponding GPR sample interval was approximately 4 in.

Each data record transmitted from the LSV to the base station contained a GPS time stamp as well as real-time estimates of the GPS coordinants relative to an accurately surveyed marker located near the east end of the surveyed area. After the field survey was completed, the real-time coordinants were refined by postprocessing the GPS data. Over most of the survey area, this reduced the location uncertainties to substantially less than 50 cm. The coordinants of the measured data were least accurate in the fringe areas of the sites where the GPS signal tended to be blocked by trees and corrupted by multipath reflections from trees and nearby water surfaces.

Four areas were surveyed on Carroll Island. The largest of these encompassed Test Grid 1 (see Figure 1) and is dominated by a large steel central tower. The magnetic field anomaly produced by this structure is clearly shown by the magnetic data on Figure 4. Also evident in the figure are a large number of anomalies that form a pattern of concentric rings around the tower. Each anomaly in these rings corresponds to the embedded base of one of many air monitoring sensors that were present when the site was being used for chemical testing. Other detected remnants of past testing activities include concrete blocks that are more or less evenly space along the outer ring, pieces of steel cable, and miscellaneous scrap material. Other magnetic anomalies shown in the figure correspond to monitoring wells that were installed after testing activities were terminated. An underground pipeline that was once used for drainage of surface water is shown by the linear anomaly in the upper right (northwest) corner of the figure. The concentration of anomalies along the north-northeast trending road near the east side of the area is probably due to an accumulation of debris in ditches along the sides of the road. The source of many small localized anomalies that are distributed throughout the surveyed area may possibly be individual UXO, which can only be determined by direct examination, but the data do not indicate that any large deposits of possible hazardous materials are present. Other subsurface deposits are to the west of the area shown on Figure 4. At these locations, the RCS survey results provide confirmation of the locations and boundaries of known burn pits and waste burial sites.

An example of the results of the metal detector (EM61) surveys is shown in Figure 5. The area includes Test Grid 2, shown in the upper central part of the figure, and the Lower Island Disposal Area, shown in the south central part of the figure (see Figure 1 for reference). The arcuate anomaly pattern at -2350 east, -1050 north corresponds to an embedded set of vertical pipes that were apparently used to support test instruments. The linear anomalies in the same general location are apparently drainage pipes. Based on prior knowledge, it was expected that buried waste material would be detected in the Lower Island Disposal Area. The geophysical surveys performed by the RCS confirmed that a large amount of metallic material is buried at that location. In fact, the anomalies shown in Figure 5 appear to represent the largest concentration of waste materials in the surveyed areas on Carroll Island. As in the area of Test Grid 1, the EM61 and magnetic sensors responded to several existing wells, a small reinforced concrete bunker, and detected a large number of small localized objects that are distributed throughout the surveyed area.

Survey results from the other two areas on Carroll Island are not shown here but are similar in character to those illustrated in Figures 4 and 5. The CS Test Area, at the eastern end of the island (see Figure 1), showed only a few magnetic or EM61 anomalies that would warrant further investigation. Several large bodies of man-made materials were detected and mapped at the VX and HD Test Areas, but these may be associated with fill material that appears to have been deposited at this location.

CONCLUSIONS

The RCS has proven to be an effective tool for site characterization at Carroll Island. The surveys described above have provided a detailed and accurate characterization of the Carroll Island sites with respect to the potential presence of large deposits of hazardous objects or materials such as UXO and CWM. By simultaneously recording data from three complementary geophysical sensors, it was able to cover the survey area quickly and efficiently. Because the three data sets were acquired simultaneously from a single platform, they represent identical areal coverage and accurate geographical registration from one data set to the next. The low ground loading of the survey vehicle minimized the possibility of detonating shallow UXO, and the single pass of the survey vehicle over the ground surface minimized the already small impact of the vehicle on the marshy sediments. Although the tires mounted on the LSV were not designed for traction in mud, the vehicle was able to negotiate the mud and standing water that covered most of the surveyed area. However, alternative survey methods must be found to negotiate and survey forested areas and the deep marshes where the current LSV can not operate.

Although chemical agents were used at the test sites on Carroll Island and some mortar shells have been found, it was not expected that either near-surface UXO or containers of chemical agent would represent a serious threat to either the vehicle or to personnel in the surveys that were performed. This assessment proved to be correct. Nevertheless, these surveys have demonstrated that the use of the RCS can greatly reduce the risk associated with the on-site activities of survey personnel while efficiently performing multi-sensor, geophysical site characterization.

The metallic content of the prototype LSV has not yet been reduced to the desired minimum level; however, the vehicle has proven to be an effective low-signature platform for the magnetic, metal detector, and GPR sensors. The principal effect of the LSV's engine and the other metallic drive train components has been a reduction in the effective sensitivity of the EM61 electromagnetic induction sensor. Follow-on improvements of the system should include the installation of pivoting front wheels on the LSV to maximize its maneuverability, implementation of stereo video to expand the visual information available to the operator, and a further reduction of the vehicles magnetic and electromagnetic signature.

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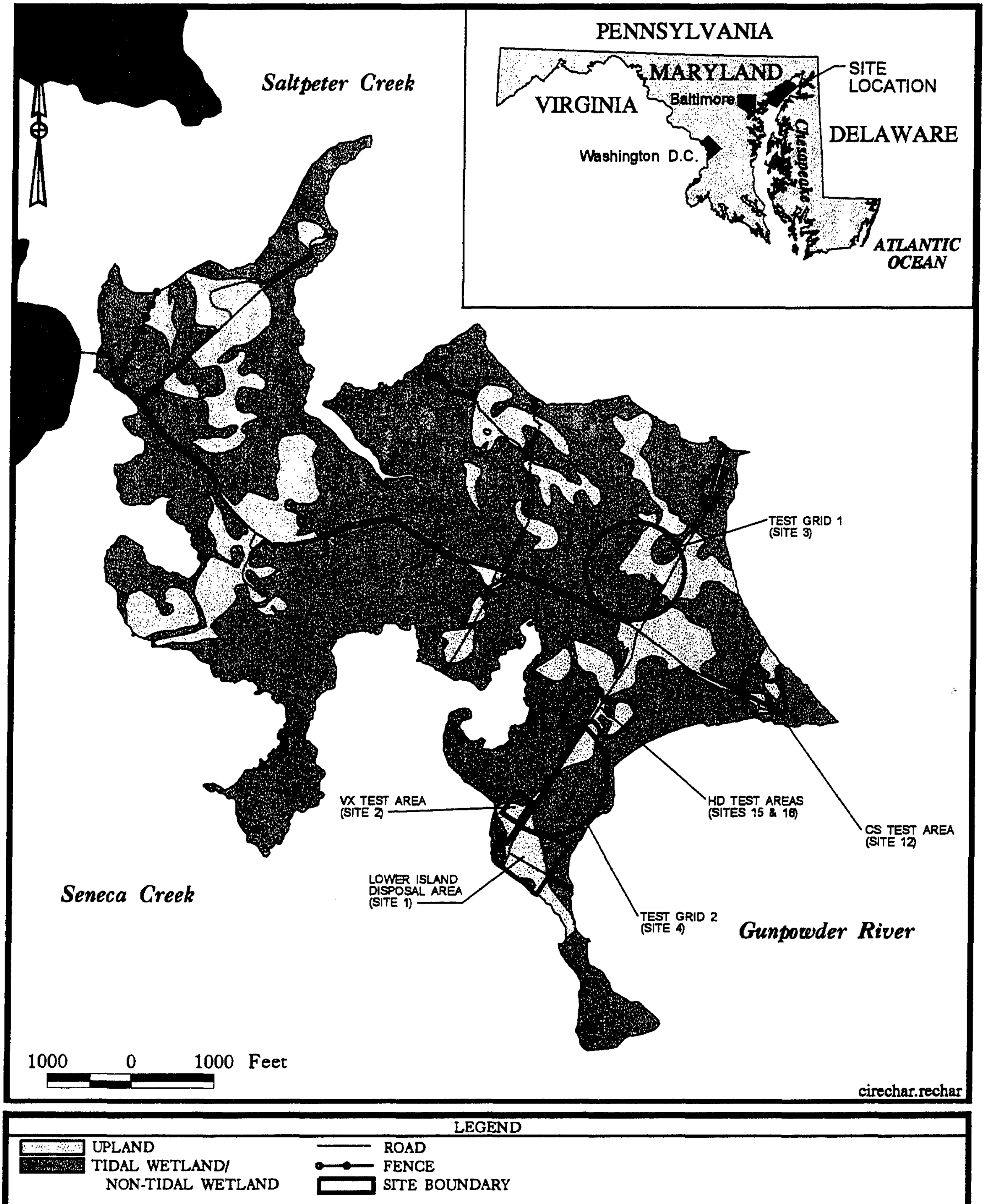

Figure 1 Carroll Island - Remote Characterization Survey Locations

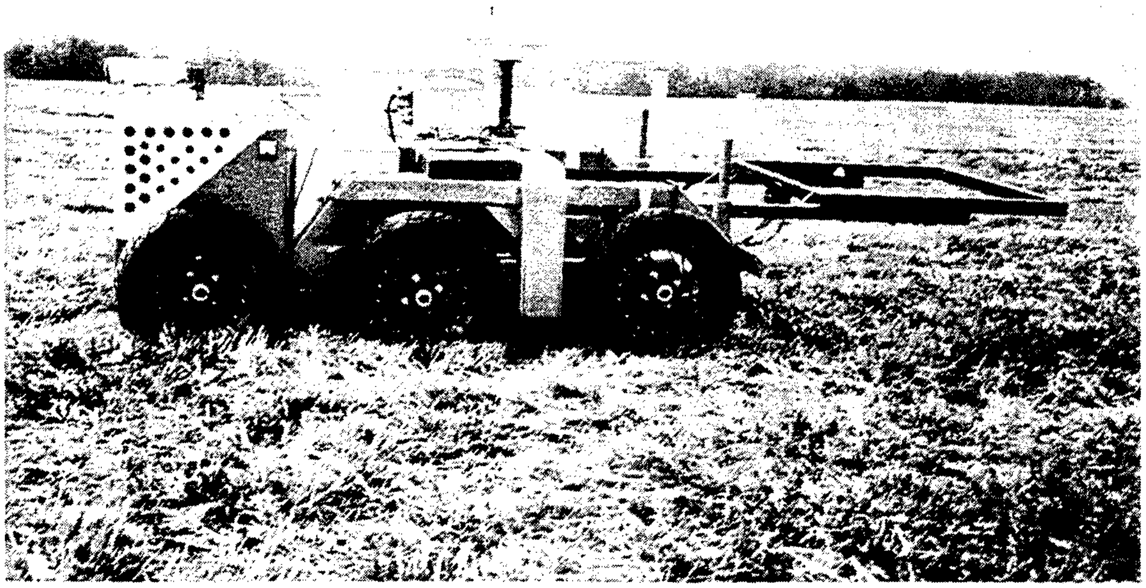

Figure 2. Low Signature Vehicle

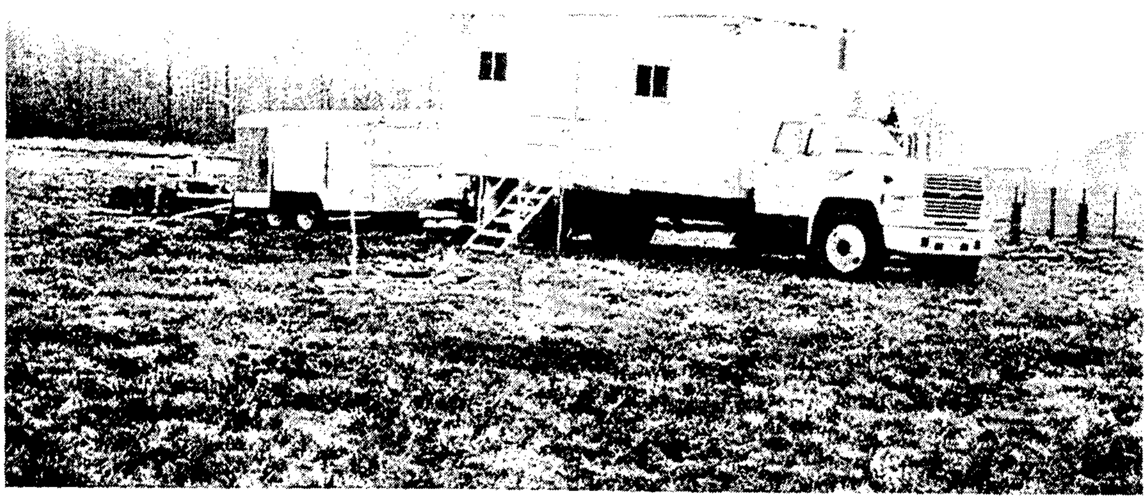

Figure 3. Remote Characterization Base Station

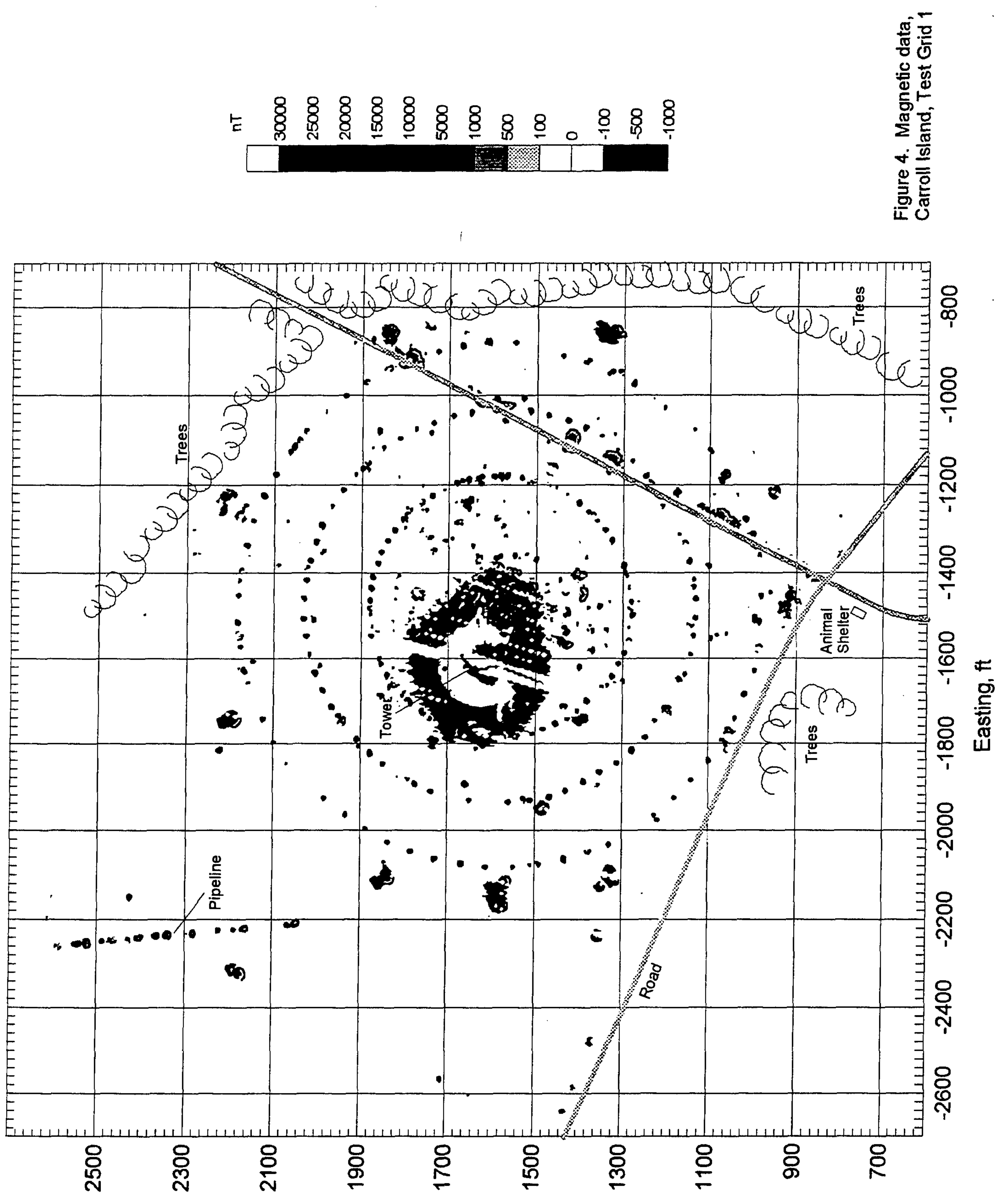

Figure 4. Magnetic data, Carroll Island, Test Grid 1

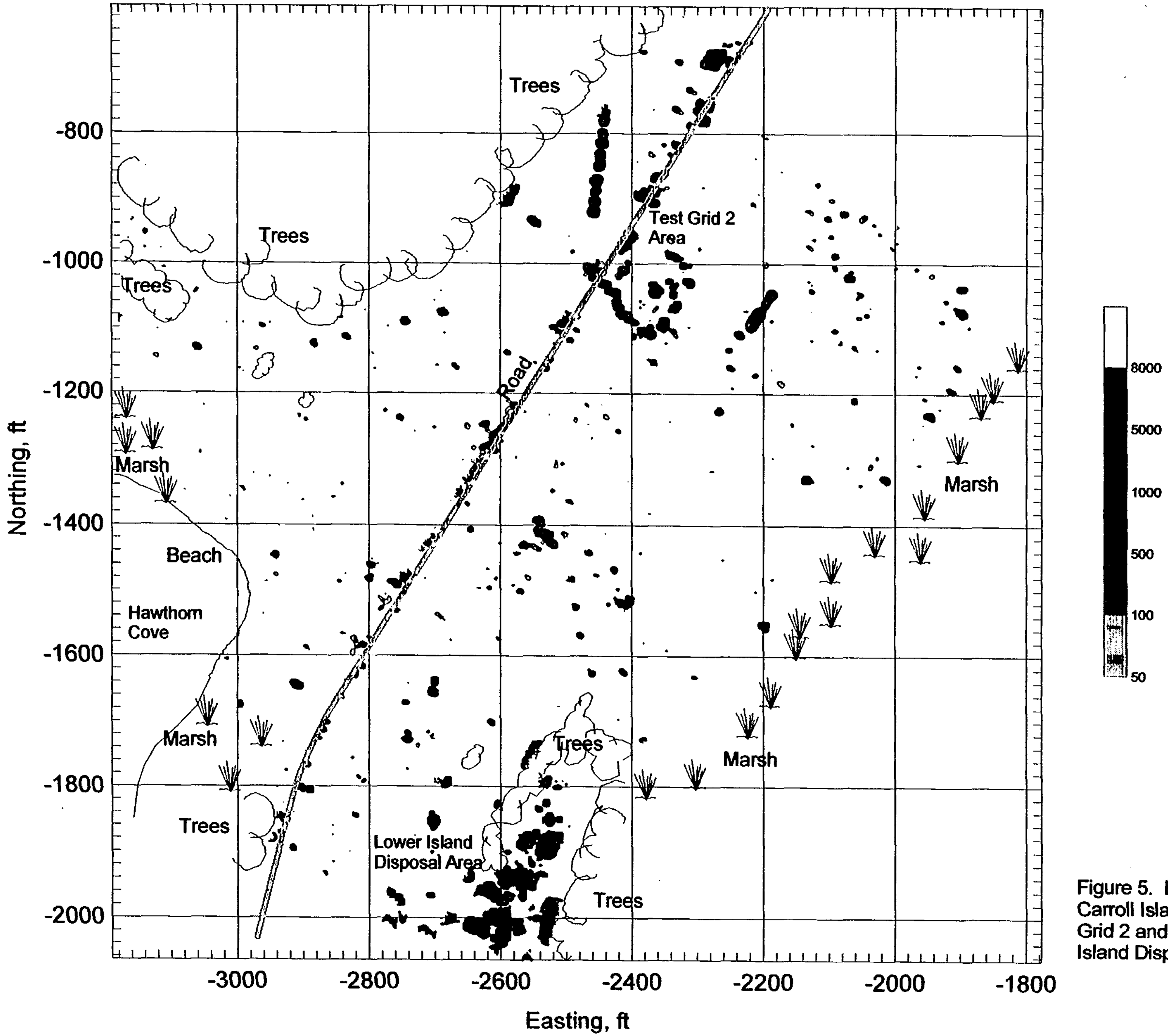

Figure 5. EM61 data, Carroll Island, Test Grid 2 and Lower Island Disposal Area

APPLICATION OF TIME DOMAIN ELECTROMAGNETIC TECHNIQUES TO UXO DETECTION

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INTRODUCTION

This paper describes initial results of an investigation into the response from typical UXO targets to time domain electromagnetic (TDEM) systems such as the Geonics EM61; a principle objective is to learn the extent to which TDEM systems can distinguish between various types of UXO and scrap metal.

The paper consists of three parts. In Part I we describe the characteristics of the Geonics EM61 TDEM metal detector as background for later discussions on the nature of target response. A following paper (Hoekstra, P., these proceedings) describes survey data taken with an EM61 at various sites. In Part II we examine the theoretical response from a variety of metal objects (spheres, plates and pipes) selected on the basis of their resemblance to typical UXO targets or metallic scrap, to understand the main features of the response, and to determine what information can be derived from it. Finally, in Part III, we examine the response from actual UXO targets.

PART I

Fig. 1 shows schematically the coil configuration of an EM61. A transmitter coil, Tx, of dimensions 1x1 m, is close-coupled with the main receiver coil, Rx1, which is also 1x1 m. A subsidiary receiver coil, Rx2, parallel with these two coils, is located 0.4 m above them. The whole array is maintained a distance of 0.45 m above the ground, either by a pair of wheels, or optionally, by an operator harness.

The function of Rx2 is two-fold: firstly having suitably adjusting its turns-area beforehand, one can subtract the output signal of Rx2 from Rx1 to substantially reduce the response from near-surface targets compared with deeper targets. Secondly, the relative signal output from the two receiver coils is compared to determine the depth to small targets (i.e. targets whose dimensions are small compared with the 1 m side length of the various coils). Since the output of Rx2 is not used for signal analysis its presence will be ignored for the remainder of the paper.

The EM61 system waveforms are shown in Fig. 2. The transmitter current initially rises exponentially to a constant value, after which it is rapidly terminated in a linear ramp, of time-duration t_o. This transmitter current causes a relatively large primary magnetic field to intercept a potential target, as shown in Fig. 1. The magnetic field is linearly proportional to the transmitter current, so that terminating the current induces, as a result of Faraday's law, a voltage in the target, which, in turn, causes current to flow in the target. This current generates a secondary magnetic field, which is sensed (along with the much larger primary field) by the two receiver coils to detect the target. From the figure we observe that, in fact, target current is induced both when the transmitter current starts and stops. Since the primary magnetic field is much larger than the secondary field, measurement is made of the target transient response only during those periods of time when the transmitter current is zero.

As shown in Fig. 2 the target current, once initiated by the transmitter turn-off, is always a monotonically decaying waveform, the maximum amplitude of which is affected by target size, shape, depth, and position relative to the coil system. The duration of the transient current is determined by target dimensions and position relative to the coil system, target electrical conductivity and target magnetic permeability. In the conventional EM61, which was designed as a simple but effective metal detector, presence of a target is detected by simply opening a time gate in the receiver 400 microseconds after transmitter current turn-off, integrating the time response over the next 400 microseconds, and closing the gate. Such a technique obviously ignores much of the information contained in the decaying current, and in this paper we will assume that the transient response is now well defined by making the measurement with a large number of narrow

time gates during the entire duration of the transient response, so that we can use the characteristics of the decaying current for subsequent analysis.

Two further points concern the material which follows. The transmitter current waveform shown in Fig. 2 is periodic, with turnoff time *to*, which somewhat modifies the target response. To avoid this complication we assume that the transmitter current waveform turn-off is a step-function with turn-off of zero time duration, as shown in Fig. 3; we will be interested in details of the time response for $t>0$. Finally, the output of the receiver coil is actually proportional to the time rate of change of the secondary magnetic field, $dB(t)/dt$, rather than to the amplitude of the secondary magnetic field, $B(t)$. The latter, being directly related to actual current flow in the target, is more useful for analysis. Fortunately it can be easily obtained, for any time t, by integrating backwards up the decay curve of $dB(t)/dt$ from $t=\infty$ to $t=t$. All calculations and measurements described in this paper will thus be of $B(t)$. All measurements were made with a Geonics TEM47 transmitter and PROTEM receiver.

PART II

In this section we examine the theoretical and measured response from three model types, selected to approximate the behaviour of both various types of UXO and trash metal. The models are a sphere, a plate, and a cylinder. Several assumptions will be made in calculating their response.

(1) It will be assumed that the response of a target buried in the ground will be essentially that of the same target in air: that is, it is assumed that there are no significant interaction effects between the target and the ground, which always has finite conductivity and often has magnetic permeability slightly larger than that of free-space. The validity of this assumption is based on the fact that the conductivity of metallic targets is always at least six orders of magnitude greater than that of the ground, and, when all is said and done, virtually all UXO targets are ferrous, with relative permeability much greater (probably by at least a factor of fifty) than the ground.

(2) It will also be assumed, to simplify the calculations, that the targets are located at sufficient distance beneath the transmitter so that the primary magnetic field can be described as being uniform in the vicinity of the target. Thus we will be interested in the dipole response of our targets.

(3) The influence of displacement currents will be ignored, justified by the magnitude of the physical parameters of typical targets, and the relatively long times at which our measurements will be made.

Sphere Response

Our first target model of interest will be a sphere, which can represent an item of UXO but more probably will represent a fragment of exploded ordnance. Its chief advantage, otherwise, is that the response, which is relatively easily calculated, illustrates features which are the same for all metallic objects. With reference to Fig. 4a we assume that the sphere, initially assumed to have conductivity σ and relative permeability $K=1$ (with respect to free-space i.e. the sphere is non-ferrous), is located in a uniform, upwards directed, vertical magnetic field B_p, which is abruptly terminated at $t=0$. Immediately after primary magnetic field turn-off, eddy currents will flow on the surface of the sphere, distributed so as to maintain the magnetic field everywhere inside the sphere at the value which existed at the instant before turn-off. As indicated in Fig. 4a this current flow, which is circumferential, is maximum at the equator and zero at the poles. The magnitude of the initial current density is determined solely by the geometry of the target, and is independent of the electrical conductivity. Since however, the sphere has finite conductivity, the amplitude of the eddy currents starts to decay, causing a decaying magnetic field in the interior of the sphere, which, as a result of Faraday's law, will induce deeper circumferential currents to flow (Fig. 4b). They, too, will decay, in turn inducing deeper current flow. This behaviour repeats itself until eventually the currents become more or less uniformly distributed throughout the interior of the sphere, whereupon the current distribution no longer varies with time. At this point the entire current distribution, now stable, simply starts to decay exponentially with time, eventually decaying to zero.

Our interest lies in the external magnetic field produced by these varying currents. Somewhat surprisingly it can be shown that this field is exactly that which would be caused by a small magnetic dipole located at the sphere center and aligned parallel with, and in the same direction as the primary field. The magnitude of this dipole, which is a function of time, can be expressed as

$$m(t)=2\pi a^3 B_p f c(t) \qquad (1)$$

where B_p = primary magnetic field at the sphere center,
a = sphere radius,

and the function $fc(t)$, shown in Fig. 5, describes all aspects of the time behaviour of the secondary magnetic field.

What can be learned from this equation? We note that if, since $fc(0)=1$, we can measure the sphere response at very early time we obtain the product a^3B_p, and since we have a way of determining the target depth (using the second receiver coil) and thus B_p, we can determine a, the sphere radius directly.

The function $fc(t)$ can be broken into three time ranges; early time, where $fc(t)$ is approximately unity (allowing us to determine a), intermediate time, about which more will be said later, and late time, at which the response becomes exponential with time, having the form $\exp(-t/T)$ where T is the characteristic time-constant of the sphere. This time-constant T is given by

$$T=\mu_o\sigma a^2/\pi^2 \qquad (2)$$

where μ_o = permeability of free-space
and σ = sphere conductivity.

We see that, having obtained a as discussed above, measurement of T allows us to calculate σ, the sphere conductivity. We have now completely defined the sphere, illustrating the power of the time-domain electromagnetic method to diagnose useful properties of conductive targets.

A further feature of the sphere response is of interest. It was stated above that the induced dipole was parallel with the primary magnetic field. As our EM61 passes over a spherical target, the direction of the primary magnetic field, and thus of the induced magnetic dipole, varies continuously with instrument location, resulting in a survey profile that is always symmetrical along the survey line.

Suppose now that we allow the sphere to be ferrous, i.e. that the magnetic permeability is no longer unity (typical values of K for iron and steel are in the range 50-200). This change has three effects on the function $fc(t)$, as shown in Fig. 6. The first is that $fc(0)$ is now a slowly varying function of K. This need not concern us, since for the range of K given above, $fc(0)\approx 3$, and we can still determine the sphere radius to reasonable accuracy. The second effect is that the intermediate zone mentioned above becomes extended in time by an amount dependent on K, and during this intermediate time $fc(t)$ now decays as $t^{1/2}$. Thirdly, once again at late time the response again becomes exponential, but now with late-stage time constant T given by

$$T=\frac{4}{9}K\frac{\mu_o\sigma a^2}{\pi^2} \qquad (3)$$

The effect of the large value of K will be to greatly increase the late-stage time constant, but note that this will be partly offset by the fact that the conductivity of ferrous metals is usually about a factor of ten less than typical non-ferrous metals.

In the material that follows we will see that the time behaviour of normal eddy current flow in all metallic bodies resembles that of the sphere. At early time the currents flow around the edge of the body, distributed in such a fashion as to keep either the internal magnetic flux or the magnetic field itself at the value that existed before primary magnetic field turn-off. At this time, measurement of the response gives useful geometrical information about the body, independent of its conductivity, but (usually weakly) dependent on its magnetic permeability. During intermediate time, the duration of which depends on K, the eddy currents decay and, at the same time alter their spatial distribution. At late time, the current distribution stabilizes, and the effective inductance and resistance of each current loop no longer vary with time; during this stage the decay becomes exponential, with a simple time-constant which is determined by the conductivity, relative permeability, and target geometry and size. We see that all stages of the response will give useful information about the target.

The characteristics of the intermediate range appear to be of particular interest, and to make this region easier to analyze (by reducing the effect of the late stage exponential decay), we have adopted the practice of transforming the data by normalizing with respect to the late stage behaviour. We do this by successively dividing the measured or calculated time function, $fm(t)$ or $fc(t)$ respectively, by the function $e(t)= A\exp(-t/T1)$, where $T1$ is adjusted until the late-stage behaviour is no longer a function of time; this value of $T1$ is therefore

T, the late-stage time constant. The value of A is then adjusted until the (non time-varying) late-stage response has the value unity. The function $ft(t)=fm(t)/e(t)$ or $ft(t)=fc(t)/e(t)$, called the transformed time-response, is used to analyze the intermediate stage behaviour.

This procedure is illustrated in Fig. 7a, where the calculated data of Fig. 5 have been transformed, resulting in a value for $T1=T$ of 2.9 msec. The two regions of the curve (intermediate and late stage) are now well separated. Furthermore replotting the transformed data as a function of t/T, as shown in Fig. 7b, clearly shows that, for a conductive sphere with K=1, the late stage commences at $t \approx T$. The same procedure was carried out on the ferrous spheres of Fig. 6; the results are shown in Fig. 8. It will be observed that, as long as K>50, the intermediate stage behaviour for all ferrous spheres is identical, decaying as $t^{-1/2}$, and that late stage is now reached at $t/T \approx 1.5$.

In the remainder of this paper we will show several measured curves of $fm(t)$ for a variety of metallic objects. Since we are primarily interested in the relative time response of the different targets, values of $fm(t)$ are given in arbitrary units and are not necessarily consistent from graph to graph. Figs. 9a, b show such data for two conductive spheres (non-ferrous and ferrous respectively). The agreement with theory is excellent.

Plate Response

Our next target model, a small thin plate, will most probably represent either a fragment of exploded ordnance or a piece of scrap metal. The data of Fig. 10 show $f(t)$ for both non-ferrous and ferrous (but otherwise similar) plates, with the primary magnetic field perpendicular to the plane of the plates. The two responses are very similar, the principle difference being that the ferrous plate shows a more steeply dipping intermediate stage decay, similar to that of the ferrous spheres. This response changes radically, however, when the direction of the primary magnetic field is altered to be parallel with the plane of the plates. In the case of the non-ferrous plate there will be virtually zero response, since the thin plate is in null-coupling with the primary magnetic field and no eddy currents are induced. There will also be no eddy current flow in the ferrous plate, but in this configuration the parallel primary magnetic field now polarizes the magnetic dipoles in the plate, causing them to line up with the primary magnetic field. When the primary field is abruptly terminated, the polarized dipoles do not return to random polarization immediately, and as they do randomize, they produce a strong, decaying secondary magnetic field, which at a distance will also resemble that of a decaying dipolar field. For the ferrous plate, when the primary magnetic field is perpendicular to the plate, polarization of the magnetic dipoles in the plate is minimal, and eddy current response predominates; when the primary magnetic field is parallel with the plate, polarization of the magnetic dipoles in the plate is optimized, and their decay dominates the response. This phenomenon is shown in Fig. 11a, from which it will be seen that at early and intermediate time the secondary magnetic field from the two types of response is almost equal; it is only at late time that the eddy current response dominates. Furthermore it is seen in Fig. 11b that, unlike the eddy current response, the polarization response never becomes exponential. In applying the transformation described above, no value of $T1$ allows the late-stage response to become invariant with time.

This phenomenon plays a very important role in the spatial response of ferrous plates, an example of which is shown in Fig. 12, which illustrates a short section of EM61 survey profile over a number of ferrous and non-ferrous objects located on the ground. As the EM61 approaches a ferrous plate, for example (b), the primary magnetic field is initially approximately parallel with the plane of the plate, and thus induces strong polarization response, with its characteristic decay. As the EM61 moves directly over the plate, excitation of polarization response ceases, to be supplanted by strong eddy current response, with different decay characteristics. As the EM61 moves on, once again polarization response dominates. The net effect of these two different responses is (a) to greatly broaden the spatial response of the plate, compared with other target types, for example aluminum plate (a), and (b) to complicate the time behaviour of the response compared with other target types. Both of these features are of great use in identifying responses from a ferrous plate. It is interesting to note that the close-coupled, horizontal coil configuration of the EM61 is ideal for identifying plate responses. The polarization response described above also occurs in the frequency domain (causing a strong quadrature phase response from null-coupled steel plates) which, because of the relatively large intercoil spacing used in devices such as the Geonics EM31, makes interpretation of such combined eddy current/polarization responses extremely difficult.

Cylindrical Shell Response

Our final target model, short sections of steel pipe, will most likely resemble UXO. We note that, like the plate

and unlike the sphere, we will have to examine the responses when the primary magnetic field is both perpendicular and parallel to the shell axis.

Before examining the time response of cylindrical shells it is necessary to digress to study the nature of the magnetostatic response of our different ferrous targets. Fig. 13 illustrates schematically the effect of placing each ferrous target in a uniform (static) magnetic field (note that placing a non-ferrous target of any shape in this field would cause no deformation of the field). The ferrous plate causes a small deformation of the uniform field, slightly increasing the magnetic flux that intercepts the plate. Recall that, when we shut off the magnetic field, the initial current that flows in the plate will just be enough to balance out this flux, and thus, as a result of flux-gathering, the initial secondary magnetic field from the ferrous plate will be somewhat larger than that from an identical non-ferrous plate, as seen in Fig. 13. This effect will be about the same for a ferrous sphere, or for a ferrous cylinder perpendicular to the primagnetic field, but if we orient a long ferrous cylinder parallel to the primary magnetic field, the flux-gathering is substantial, and we thus expect that the initial response from a ferrous cylinder (or cylindrical shell) oriented parallel to the primary magnetic field will be much larger than from the same cylinder perpendicular to the field.

Fig. 14 shows the response from one of the steel pipes with both orientations of the primary magnetic field. The effect described above is immediately noticeable. However another effect is also evident; during the intermediate time the decay rate, when the shell axis is parallel to the primary field, is much more gradual than when perpendicular. This appears to be due to the fact that the transient secondary magnetic field is now being caused both by decaying eddy currents and decaying polarization, the effects of which are additive.

PART III

We now examine the time response from a series of five pieces of UXO. These consist of (a) a 40 mm shell, (b) a 60 mm M2 mortar round, (c) an 81 mm mortar round, (d) a 105 mm M14 shell, and (5) a 155 mm M107 shell.

Note that these items most nearly resemble our cylindrical steel pipes, but that they have different dimensions (both length and diameter), and also differ in that they have pointed noses and in some cases taper down to small tail assemblies.

Results from the individual shells are shown in Figs. 15a-e, where we note that, in all cases where the primary magnetic field is parallel rather than perpendicular to the shell axis, thus inducing solenoidal current flow, (a) the early stage response is greater, (b) the intermediate stage decays more slowly, and (c) the late-stage time constant is larger. These are significant differences since, in general, the axis of such a shell will lie at an arbitrary angle with respect to the direction of the primary magnetic field, which will therefore have components both parallel and perpendicular to the shell axis. Both components will excite the appropriate eddy current flow, but if measurement of the total response is made out to sufficiently late time, in nearly all cases the limiting response will be caused by solenoidal current flow. Measurement of the various spatial components of the response will then yield the orientation of the shell (note that for this type of anomaly the profile will generally be asymmetrical along the survey line). Furthermore, the late-stage time-constant may be reasonably specific to a given shell since it will depend on, amongst other factors such as steel permeability and conductivity, the internal structure of the shell, specifically to different variations of shell wall-thickness.

Finally, Fig. 16 shows detailed behaviour of the intermediate time response for each of the shells, as exemplified by the transformed time responses. It is noted that this response is quite different for the various shell types. Once the orientation of the shell has been established from the late stage measurements, the intermediate time response can be separated out, and this feature too may well prove to be diagnostic.

Conclusions

It is probably unlikely that, in a blind test, a TDEM survey would be able to specify the nature of subsurface targets sufficiently well to identify different types of UXO. Furthermore our measurements have only been of UXO that was cylindrical by nature. Nevertheless, given "a priori" knowledge of the decay characteristics of UXO that are expected in a survey area (specifically, the value of $fm(0)$, the nature of the intermediate time behaviour, and the value of the late-stage time-constant), the evidence presented in this paper suggests that it might be possible to separate out various types of UXO (a) from each other and (b) from exploded ordnance and other trash metal. Further measurements are certainly necessary to confirm the extent of this possible uniqueness. At the least it would appear that the TDEM technique offers more promise for identification of UXO

than techniques based on potential field theory.

Acknowledgements

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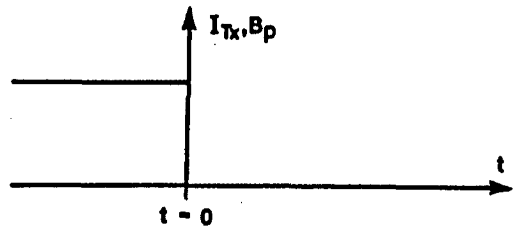


Fig. 3 Step function current

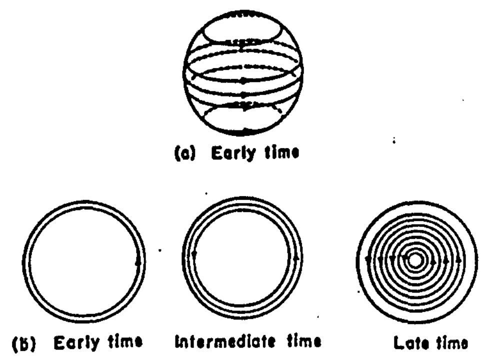


Fig. 4 Decaying sphere currents

FIGURES

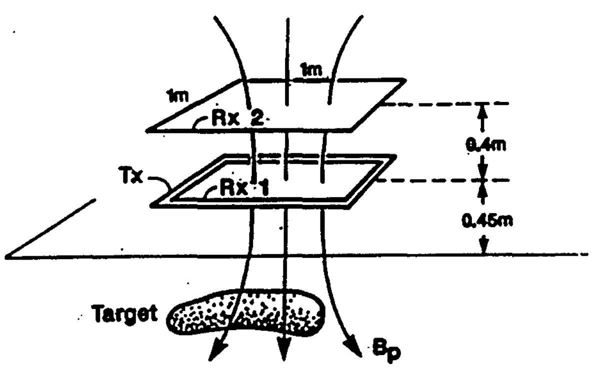


Fig. 1 EM 61 coil configuration

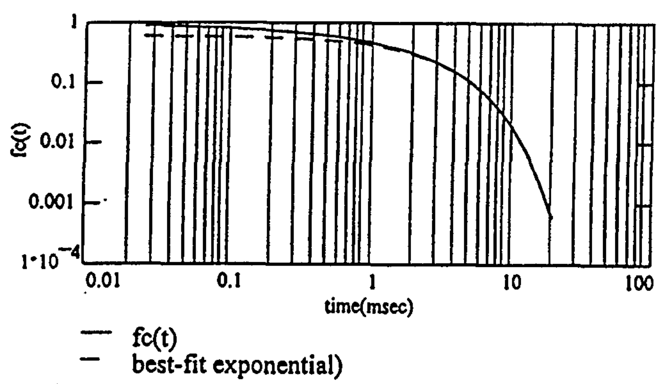


Fig. 5 Non-ferrous sphere response

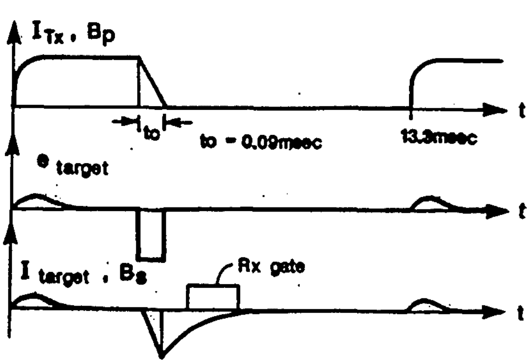


Fig. 2 EM 61 waveforms

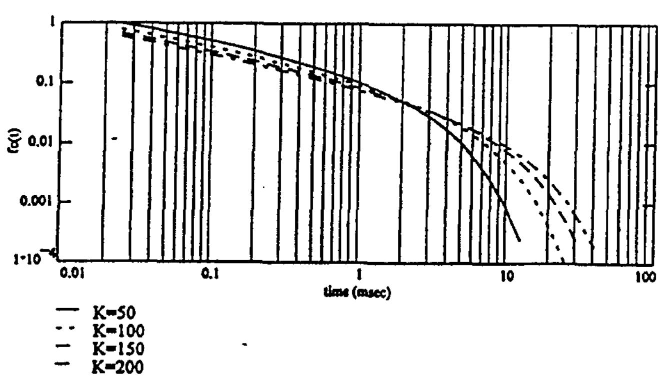


Fig. 6 Ferrous sphere response

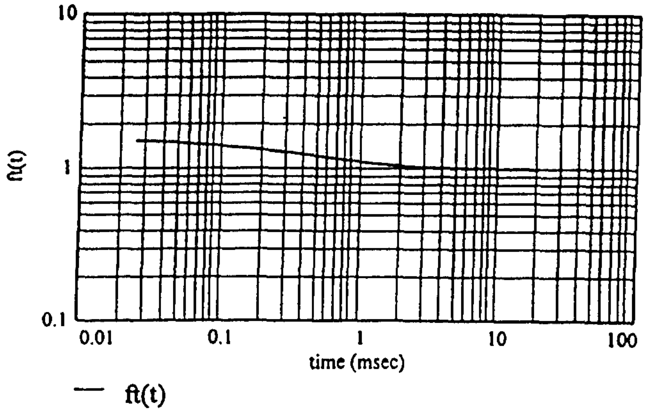


Fig. 7a Transformed response

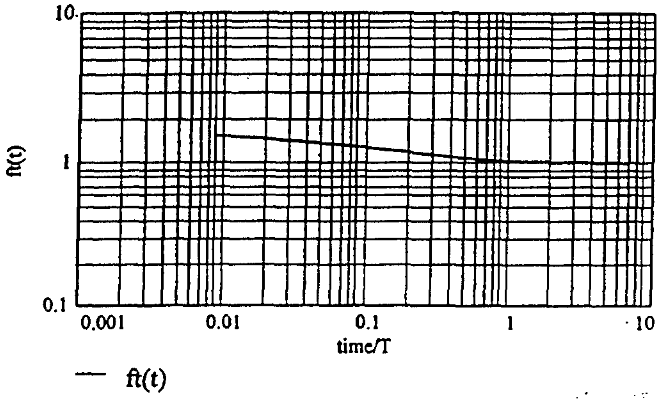


Fig. 7b Transformed response

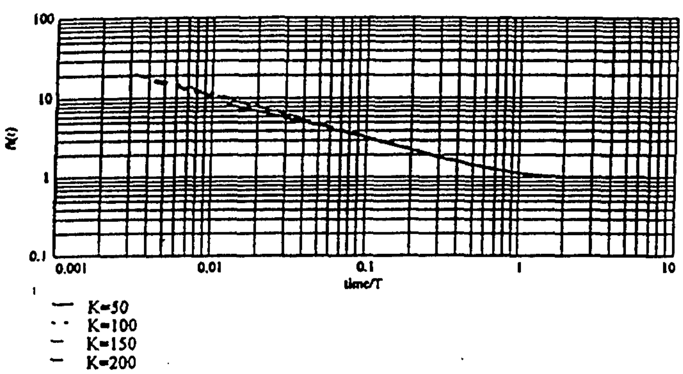


Fig. 8 Transformed response

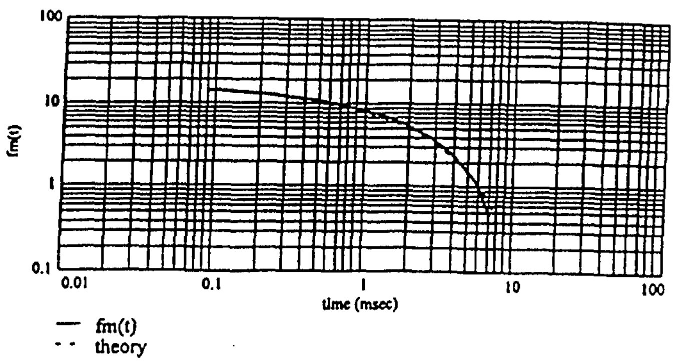


Fig. 9a Non-ferrous sphere response

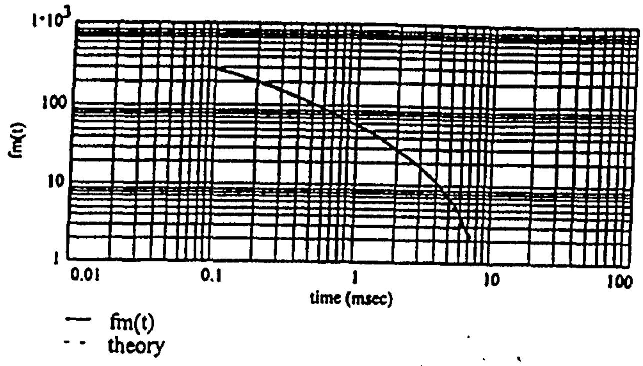


Fig. 9b Ferrous sphere response

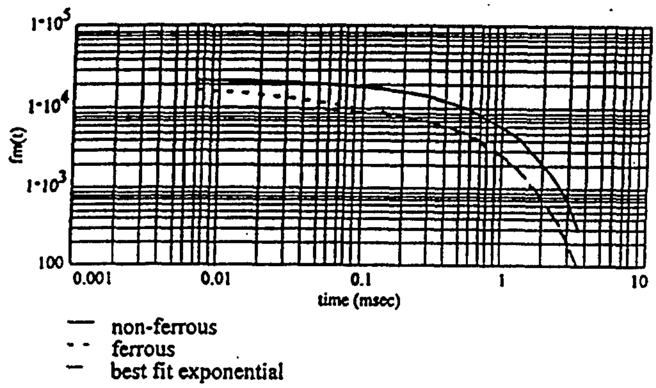


Fig. 10 Plate response

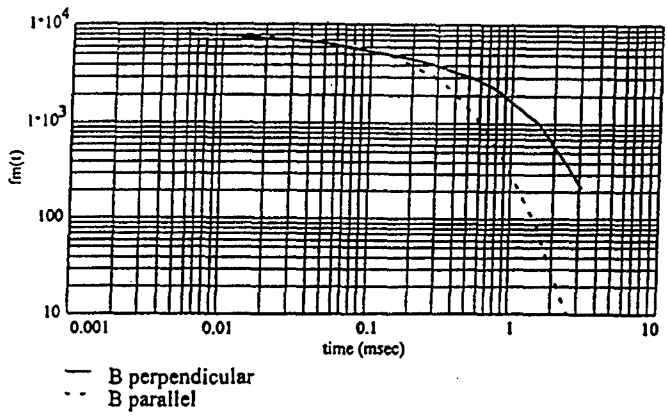


Fig. 11a Plate response

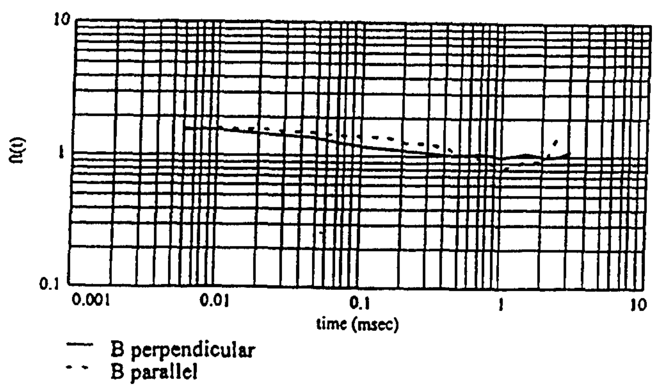


Fig. 11b Transformed response

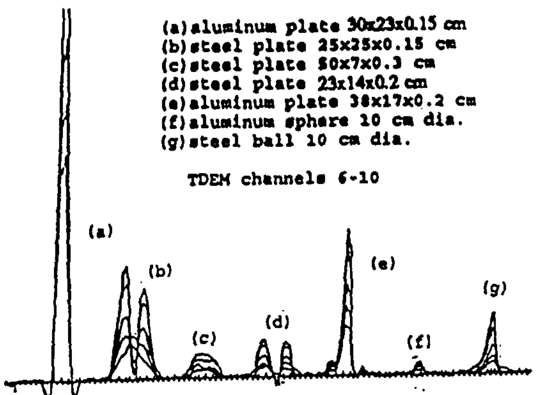


Fig. 12 Survey profile

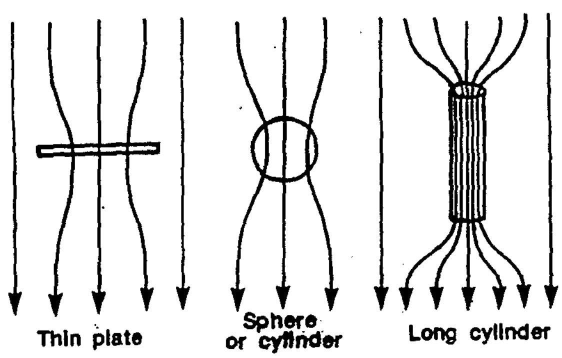
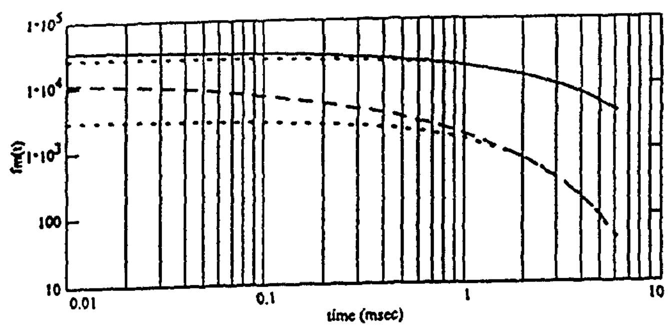
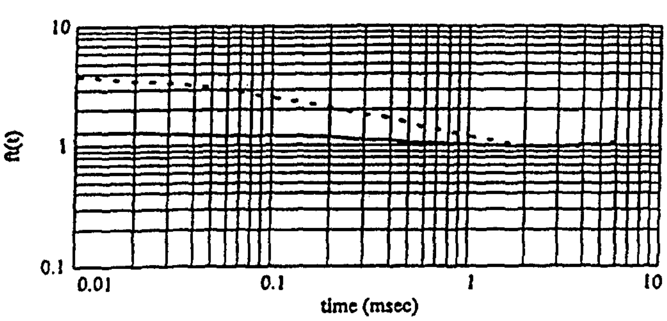


Fig. 13 Flux gathering



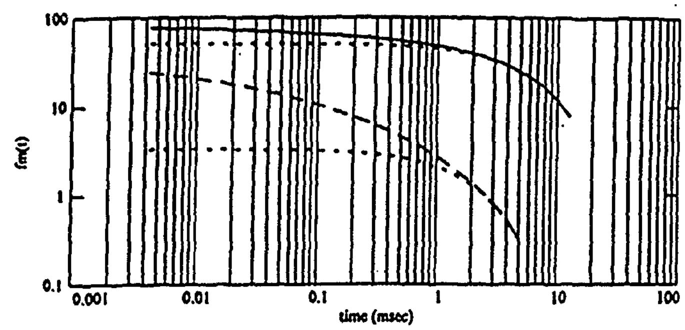
— B parallel
— B perpendicular
- - best fit exponential
- - best fit exponential

Fig. 14a Pipe response



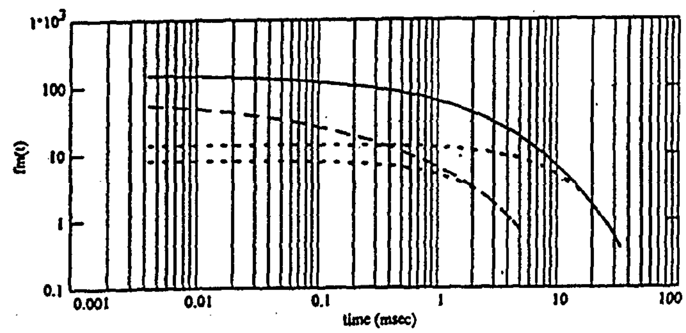
— B parallel
- - B perpendicular

Fig. 14b Transformed response



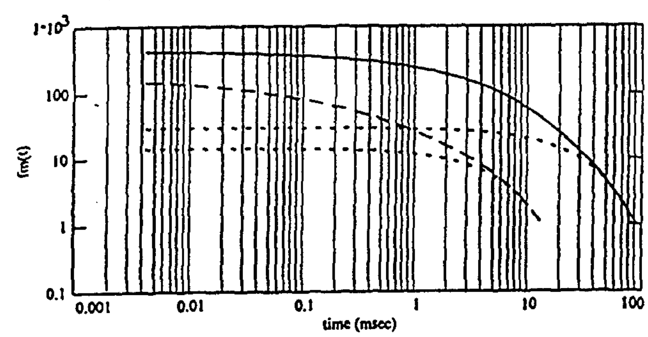
— B parallel
— B perpendicular
- - best fit exponential
- - best fit exponential

Fig. 15a 40mm shell response



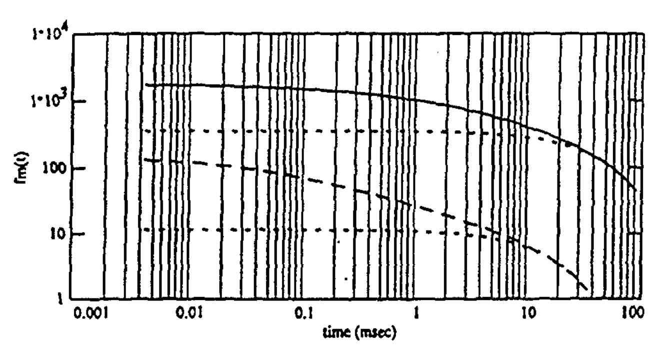
— B parallel
— B perpendicular
- - best fit exponential
- - best fit exponential

Fig. 15b 60mm M2 mortar response



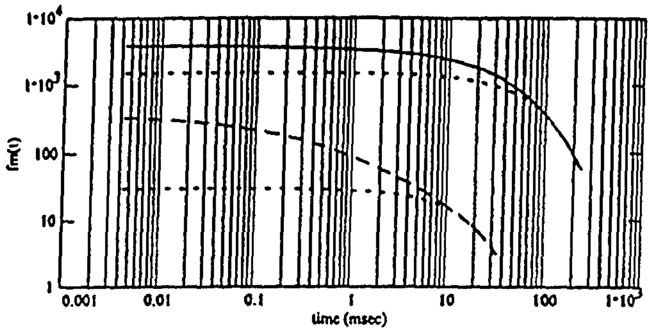
— B parallel
— B perpendicular
- - best fit exponential
- - best fit exponential

Fig. 15c 81mm mortar response



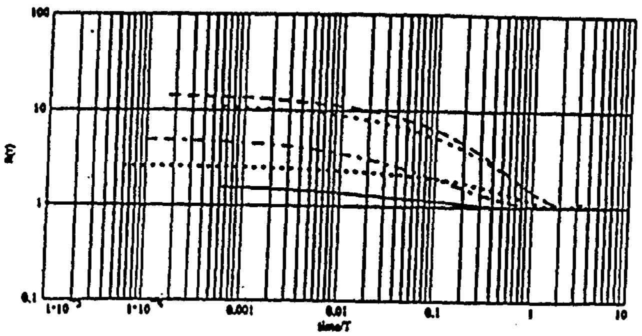
— B parallel
— B perpendicular
- - best fit exponential
- - best fit exponential

Fig. 15d 105mm M14 shell response



— B parallel
– B perpendicular
- - best fit exponential
- - best fit exponential

Fig. 15e 155mm M107 shell response



— 40 mm shell
·· 60 mm M2 mortar
– 81 mm mortar
– 105mm M14 shell
·· 155 mm M107 shell

Fig. 16 Transformed responses

PULSED ELECTROMAGNETIC INDUCTION AS A UXO DETECTION TECHNOLOGY

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ABSTRACT

The high false alarm rate in unexploded ordnance (UXO) detection using standard magnetometric, electromagnetic induction, and radar methods motivated a study to evaluate the use of a Pulsed ElectroMagnetic Induction method (PEMI) for localization, characterization, and identification of UXO. It is well known in geophysical prospecting applications that the PEMI method can provide more information about the conductive target than is available using continuous wave techniques and thus would likely be useful in distinguishing between different objects encountered in a UXO contaminated site. Carried out in FY95, the project included development of a complete set of PEMI models for simulation and data reduction, development of a testbed PEMI system and data processing tools, and several stages of field work in which the models were validated and responses from several inert UXO samples were measured. The project results indicate that the PEMI method has significant potential for use in UXO target discrimination. This paper presents an overview of the results obtained in the project.

INTRODUCTION

The UXO Problem

Millions of acres of US Government property are contaminated with unexploded ordnance (UXO) as a result of weapons testing and troop training activities conducted over the past century at Department of Defense sites. The type and concentration of UXO present at these sites varies greatly, as do geological, environmental, and topographical site characteristics. The risks to human health and the environment associated with this contamination has driven the need for technologies that can detect, locate, classify, identify and remediate buried UXO in a safe, accurate, and cost-effective manner. In response to this need, the US Army Environmental Center (USAEC) has established the UXO Clearance Technology Program. The objective of this program is to assess and advance the state-of-the-art in UXO identification, characterization, and remediation technologies.

USAEC responds to joint service UXO needs by investigating applicability of a variety of technologies toward the UXO problem. USAEC has designated the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) as the technical lead for the UXO Clearance Technology Program. As part of this effort, the NAVEODTECHDIV has pursued enhancements in detection technologies, data analysis, and processing techniques. This paper presents an overview of a 12 month effort to investigate the use of Pulsed ElectroMagnetic Induction (PEMI) in detecting, locating, and characterizing buried UXO.

Electromagnetic Sensing Technologies

In recent years, much progress has been made in improving sensing and remediation technologies for use in all phases of UXO cleanup. Magnetometers (which measure the total magnetic field at a specific location) have been used for decades in UXO detection, but their use in arrays to measure the magnetic field gradient has greatly improved their effectiveness. The advent of Ground Penetrating Radar (GPR) for detecting UXO has raised the hope that a remote sensing imaging technique will be available for use from aircraft for safe operation and rapid area coverage; unfortunately, the GPR method is still under development and is not yet practical. Perhaps surprisingly, fundamental improvement in electromagnetic induction techniques has been slower in coming. For many years the continuous wave "metal detector" has been the standard electromagnetic induction tool for UXO work, though development of advanced electromagnetic induction methods for geophysical prospecting has been occurring for many years. Specifically, pulsed (broadband) electromagnetic induction methods have been shown to have several advantages over continuous wave (single frequency) techniques, the most important of which is the

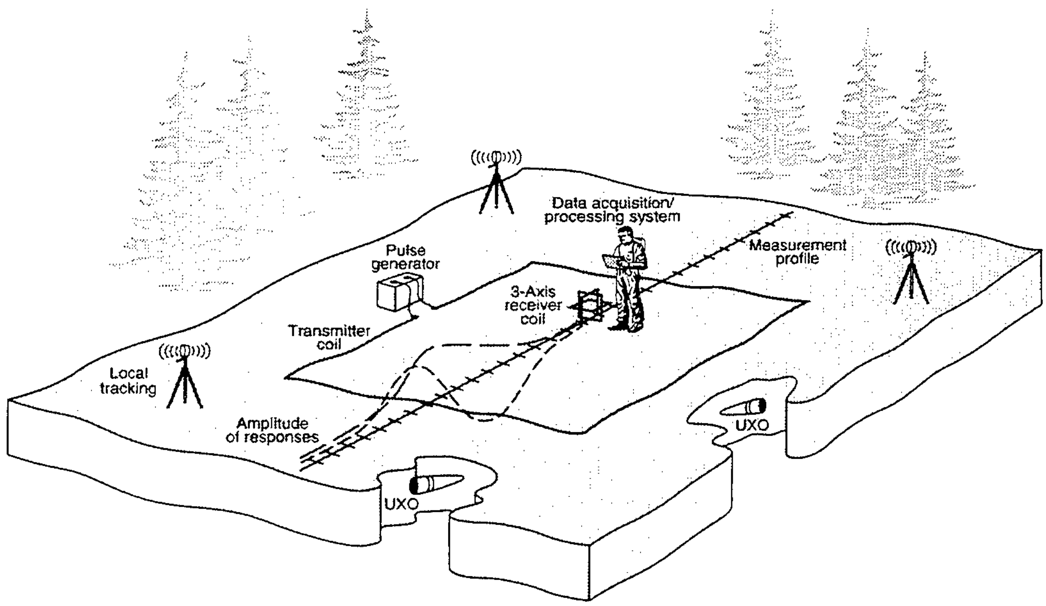

Figure 1. Artist's conception of a possible field implementation of the PEMI method.

ability to discriminate between objects of different conductance (conductance is defined as the product of an object's length in the direction of interest by its conductivity). This discrimination ability does not depend on the relative depths at which the objects are located. For the geophysicist, this permits detection and characterization of an ore body buried beneath conductive overburden which might otherwise shield the ore body from detection. For the UXO remediation technician, the ability to classify targets lowers the false alarm rate and hence the cost of cleanup. The PEMI method works by exciting transient eddy currents in a conductive target by electromagnetic induction, and uses the measured decay rates of these currents to characterize the target. While the temporal characteristics of the magnetic field associated with the eddy currents in the target are used for classification, the spatial characteristics of the field are used to locate the target.

Applying PEMI to UXO detection

The application of the PEMI method used in geophysical mineral exploration (where it is called the Time Domain ElectroMagnetic (TDEM) method) to the detection, location, and characterization of UXO is promising because metallic targets are particularly well suited to the PEMI approach. The very large electrical conductivity contrast (and often large magnetic permeability contrast as well) between metals and soil is advantageous. Unlike for mineral deposits, the characteristic decay time constants for UXO targets are very long compared to the typical earth response; consequently UXO eddy currents persist far longer than earth currents. Furthermore, UXO targets confine their eddy currents to a very small volume compared to the physical extent of the induced eddy currents in the earth; thus the spatial characteristics of the UXO magnetic fields are very different from the spatial signatures of earth fields. For practical purposes, UXO PEMI data interpretation only involves separating responses from different metallic targets because the earth's response can be neglected to a very good approximation. UXO decay time constants cover a wide range of time scales because of a wide range of ordnance sizes and construction styles, and PEMI measurements of these time constants often makes target discrimination possible even in the case of multiple targets with mixed sizes and depths.

Current commercial PEMI devices have not been optimized for the UXO detection and discrimination application. The project's objective was to collect data from real UXO targets and evaluate the PEMI method. A commercial geophysical transmitter was successfully used along with a laboratory data acquisition system in the one year program described here. The field operational layout of the PEMI method in this evaluation program was based on the geophysical survey geometry used in mineral prospecting for conductive ore bodies, but the scale of transmitter and receiver coils was reduced to better match the size of typical UXO targets.

Figure 1 presents an artist's conception of the PEMI method implementation used in this program. A transmitter energizes a coil laid out on the surface of the ground with a pulsed current waveform that closely resembles a square wave. The rapid changes in magnetic field occurring at the edges of the waveform, that is, at transmitter turn-on and turn-off, induce eddy currents in nearby conductors. The receiver, comprised of a set of coils, amplifiers and digitizers, is carried by a technician along a surface profile. Ideally (though not implemented in this program) real-time processing combines position information (obtained from a local tracking system or differential GPS) and PEMI data to provide a map of the type and location of any detected object. It is certainly conceivable that the transmitter electronics and coil could be carried along with the receiver in a practical system. If the survey zone is not considered safe enough for a

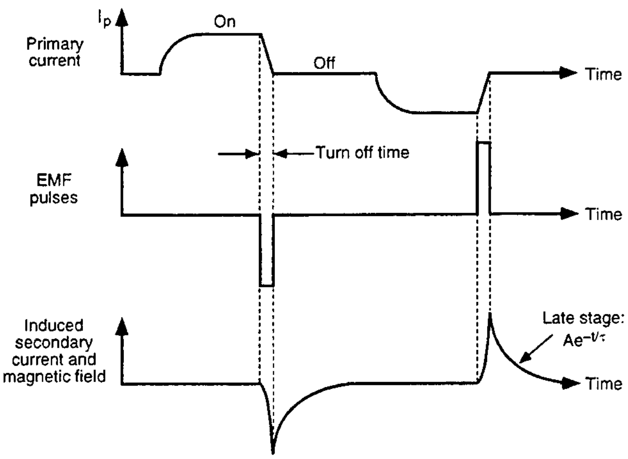

Figure 2. PEMI waveforms: current in the transmitter (primary), emf near the transmitter, and current induced in the conductor (secondary).

technician, the PEMI system could be developed for use on a remotely operated vehicle.

THE PEMI METHOD

Electrical currents can be readily induced in conductors by immersing them in a (primary) time varying magnetic field. These induced currents in turn create secondary magnetic fields which can be detected in the region near the buried conductor. The temporal and spatial variation of these secondary magnetic fields contain information about the conductor, such as its position, size, and conductivity. Studies have shown that pulse methods provide more information about the target than do single frequency methods, especially important when the response is cluttered by other conductors lying closer to the sensor. Much of the original development of the pulse induction method was done by Kaufman [1978a, 1978b]. McNeill [1980] presents a succinct exposition of the PEMI method's applications in the context of geophysical prospecting.

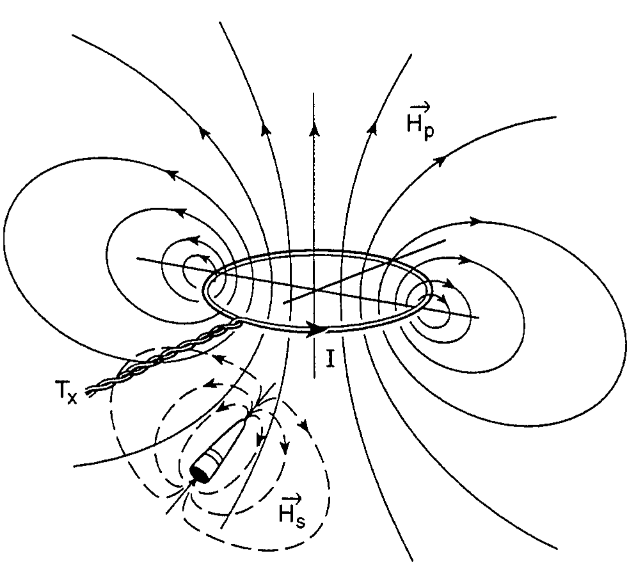

Figure 3a. PEMI geometry indicating the primary coil driven by a transmitter (Tx) to produce coil current I and the primary magnetic field $\mathbf{H_P}$. After turn off, induced currents in the UXO create the secondary field $\mathbf{H_S}$.

Primary and secondary fields

The primary current in the transmitter coil is a series of pulses as illustrated in Figure 2. During the transmitter "on" time, the current in the transmitter loop reaches a constant value, creating a constant primary magnetic field in the vicinity of the target conductor. The primary magnetic field exists in all space but is strongest near the transmitter, as indicated by the density of field lines in Figure 3a. When the transmitter current (and thus the primary magnetic field) is turned off abruptly, a large electromotive force (emf) pulse arises in space by Faraday's law. The emf drives a current pulse in the conductor. This induced current is such that the magnetic field within the confines of the conductor is the same as it was just before turn off. Immediately after the emf pulse, resistive losses cause the secondary currents to decay with time, leading to induction of other currents further inside the target.

Three stages of the pulse response

The pulse response of a confined conductor is conveniently divided into three time intervals, each of which corresponds to a different physical regime. At turn off, currents form on the outside of the conductor in such a way as to exactly preserve the magnetic field that was inside the conductor before turn off. In the very early instants after turn off, the induced currents are confined to the outermost parts of the conductor. This is consistent with the idea that early times correspond to very high frequencies, and at high frequencies the skin effect prevents currents from penetrating into the conductor. In this **early time** stage, it is clear that the current distribution depends on the primary field and on the external shape of the conductor, but is independent of the target's conductivity.

The surface currents are soon attenuated by resistive losses, and because they change with time they begin inducing other currents circulating further inside the conductor; as time progresses, the distribution of currents changes to include the entire conductor. This diffusion of currents happens during the **intermediate time** stage.

In the **late stage** however, the spatial distribution of currents in the conductor no longer changes, and all currents merely decay at the same exponential rate. The time constant characterizing this late stage exponential decay is determined by the overall construction (shape, material conductivity and permeability) of the body. In the case of metallic objects made from the same metal the conductivity is the same; consequently, only the shape determines the exponential time constant. For solid cylindrically symmetric bodies, a simple conductive loop circuit with inductance L and resistance R, is often a

satisfactory late stage model; see Figure 3b. Indeed, a current in such a loop decays exponentially, with decay constant $\tau = L/R$. The late stage behavior for confined conductors allows straightforward characterization of the conductor from measurements of the secondary magnetic field which decays with the same exponential time dependence.

The *amplitude* of PEMI target responses depends on transmitter and receiver coil location and orientation, but the *time rate of decay* of the response does not (barring special geometric cases in which the object and field are precisely aligned so as not to excite the fundamental mode of the target's response). The decay rate depends only on important intrinsic (and macroscopic) target parameters such as shape and conductivity, and can thus be used to discriminate quantitatively between different objects.

Kaufman [1978a] showed that the complete pulse response of a conductor of finite extent is given by a sum of decaying exponentials with a range of time constants. The late stage begins when the term with the longest time constant dominates the response. Graphically, the logarithm of the magnitude of the secondary field versus time tends asymptotically to a straight line in the late stage; the slope of the line gives the late stage decay constant.

Measuring the secondary magnetic field with a coil antenna results in an additional time derivative because the voltage at the terminals of the receiver coil is proportional to the emf induced in the coil by the

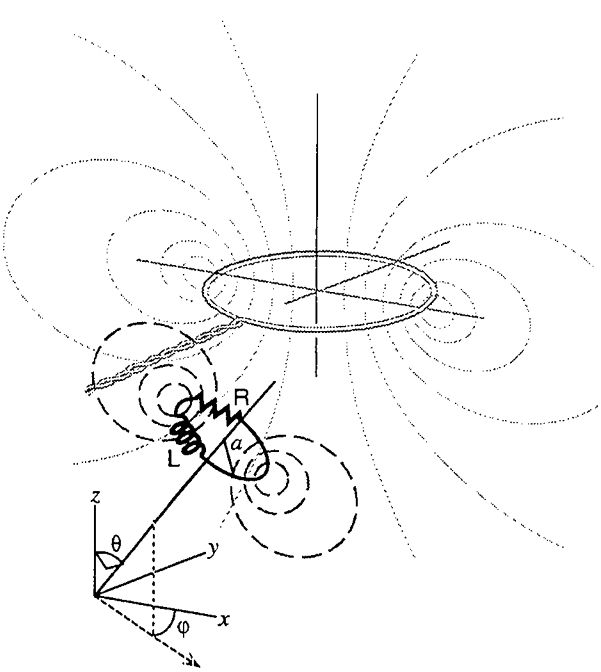

Figure 3b. The thin ring circuit is used to model the response of a confined conductor such as a UXO. There are 7 ring model parameters: position (x, y, z), orientation (θ, φ), inductance *(L)*, and resistance *(R)*, with decay constant given by $\tau = L/R$.

secondary field. Consequently, the magnitude of confined conductor responses is modified by a factor of $1/\tau$, augmenting short time constant responses and diminishing long time constant responses.

PEMI MODELS

The PEMI method has been extensively developed for mineral and oil exploration applications. In adapting the PEMI method to the UXO detection and remediation application several models are needed for PEMI system design, and for data interpretation. We distinguish between *forward* models, which allow computation of primary and secondary fields given transmitter, receiver, and target characteristics, and *inverse* algorithms which use the forward models to produce estimates of target properties from survey data. Forward models provide a PEMI simulation capability while inverse schemes provide a means of analyzing and interpreting PEMI data.

Primary Field

The primary field model computes the magnetic field at any point in space due to a constant current in a transmitter antenna, usually a coil of wire. Expressions for three specific loop types are implemented: a magnetic dipole, a circular loop of finite radius, and a rectangular loop. The governing equation for magnetostatic fields is the Biot-Savart law which relates the magnetic field at any point in space to its source, here the transmitter current. It is important to recognize that the frequency range of PEMI (and all inductive techniques) is low enough that all electromagnetic propagation effects are negligible; thus, the permittivity never enters into the field calculations.

Target Response

The simplest model for the late stage current distribution is a thin circular conductive loop, characterized by radius a, resistance R and inductance L, its position in space (x, y, z), and two orientation angles θ and φ. The thin loop or ring model captures many of the late stage characteristics of the response of a solid confined conductor. In most cases, the parameters $(R, L, a, x, y, z, \theta, \varphi)$ of the simple oriented loop circuit illustrated in Fig. 3b represent "effective" target parameters, used to parameterize the late stage response of an object much more complex in shape and composition than the simple loop.

The extinction of the primary field creates an emf in a target conductor proportional to the flux Φ_P through the conductor. The flux in the thin loop model is simply obtained by evaluating the primary field in the center of the loop and taking the dot product with the loop area vector.

The secondary current I_S induced in the loop then decays exponentially as

$$I_S(t) = \frac{\Phi_P}{L} e^{-t/\tau}.$$

Secondary Field Model

The secondary currents induced in the target conductor produce a secondary magnetic field. As the currents decay, the secondary magnetic field decays as well, creating a secondary emf which can be measured by a receiver coil. The secondary field model first computes the current induced in the oriented loop as above, then evaluates the field due to the loop current at the center of the receiver coil. This last step is done using the computer codes developed for the primary field model but here the problem is complicated by the orientation angles of the loop which rotate the coordinate system of the loop target with respect to the survey coordinate system. Both the secondary magnetic field vector components and the receiver location coordinates have to be transformed.

Background Earth Response

A simple late stage expression [Kaufman and Keller, 1983] for a homogeneous half space was used to estimate the earth response for experimental planning purposes. Both the model and the data from UXO measurements presented below indicate that the earth response is generally negligible in UXO prospecting. However, discrimination of small UXO objects such as antipersonnel grenades or mines which have time constants shorter than a few milliseconds may require estimating the earth response so that it can be taken into account during data processing. It is important to emphasize that during the time of the UXO response the currents in the earth will be relatively far from the transmitter and hence will create a field which is nearly uniform over the UXO detection zone.

PEMI DATA PROCESSING

PEMI data is comprised of sets of short time series in which the secondary magnetic field decays are recorded as time varying voltage values. The recordings are taken at several stations, usually along a profile or on a grid, providing a set of measurements which is both spatial and temporal. The receiver is synchronized with the transmitter turn-off so that many pulses are recorded and coherently averaged at each station to reduce the effect of ambient electromagnetic noise. Other noise reduction schemes such as synchronizing the pulses to the local power grid frequency or using an auxiliary sensor to independently measure correlated ambient electromagnetic noise have been used in our approach but will not be described here. Instead, we will emphasize the algorithms used in data interpretation.

For convenience and speed, the inversion of PEMI data is done in two steps. First, the time decay is analyzed at each station to determine whether an exponentially decaying response is detected, and if so, to estimate the time constant and amplitude factor of that late stage decay. Once the amplitudes have been determined for all stations, their spatial dependence is used to estimate the location and orientation of the target conductor. The late stage response is simply modeled as

$$R(t) = A(r)\, e^{-t/\tau}$$

where the amplitude $A(r)$ includes the factor of τ in the denominator. The challenge with real data is to determine when the decay has reached the late stage, and when the ambient noise level has exceeded the PEMI signal (see Figure 7); in this project, selection of the appropriate time interval was usually done by an operator, but the experience gained will facilitate the design of automated detection algorithms.

The approach used to make the estimates of decay constant and target location was to fit the thin ring model to measured responses using a non-linear Damped Least Squares (DLS) optimization routine [Marquardt, 1963], which provides an automated and stable way of finding the "best" fit of the simple ring model to the data. Other optimization algorithms could be used as well, so long as they were able to handle non-linear inverse problems.

Comment on multisensor noise reduction tests

The PEMI project was done with the collaboration of Alliant Techsystems on their grounds in Mukilteo, Washington. Alliant was primarily evaluating other methods for UXO detection and discrimination such as GPR and concepts for data fusion, but they also suggested PEMI noise reduction tests using auxiliary sensors. The idea was to try to cancel magnetotelluric signals by measuring them independently with a sensor (or sensors) that is out of the field of the UXO target. Magnetotelluric fields originating from distant sources are expected to be highly correlated over the short distances encountered in a PEMI survey. However, the effect local inhomogeneities (such as UXO targets) have on these geophysical fields may be similar to those exploited in magnetometric surveys. Tests were performed in which ambient fields measured by an auxiliary sensor about 10 meters away from the target area were used in an adaptive cancellation scheme. At best, noise reduction of 7 to 10 dB was obtained; typical noise reduction was less than 5 dB and such improvement was not deemed sufficient to warrant further investigation in the course of this project.

PEMI SYSTEM TESTBED

The PEMI hardware system is composed of three principal parts: the transmitter, the receiver, and the data acquisition computer system. The heart of the Data Acquisition System (DAS) is a Macintosh Quadra 900 computer with two National Instruments NB-A2150 analog to digital converter cards, and a GPIB interface card which provides a communication bus for remote control of the receiver amplifiers and the transmitter

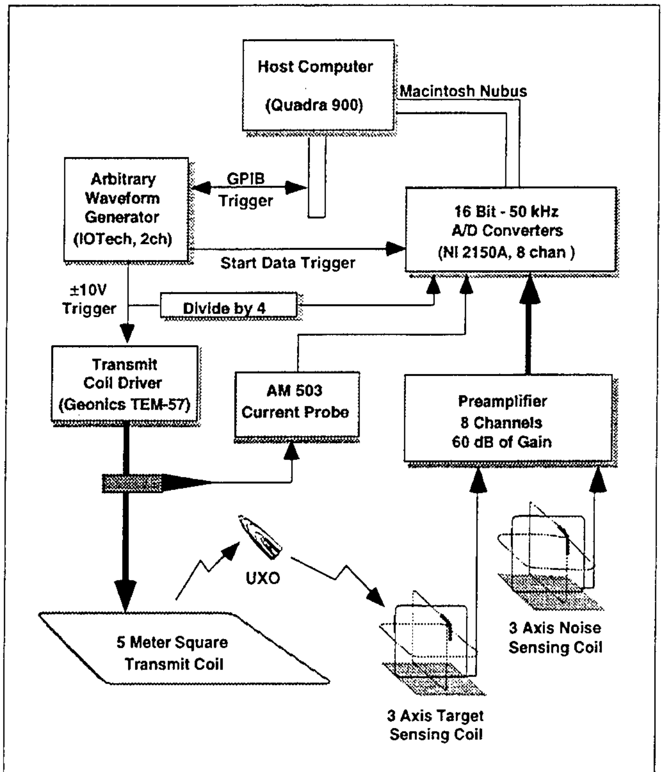

Figure 4. PEMI data acquisition system diagram.

trigger waveform generator. The system is controlled by a program written in LabVIEW™, a graphical instrument control language available from National Instruments. This program controls the entire PEMI data acquisition process, including sending out the transmitter triggers, digitizing the amplified receiver voltages, displaying the data upon acquisition, and finally storing the data to disk for later retrieval and processing. A block diagram of the PEMI hardware is presented in Figure 4. The data processing is usually done on a separate Macintosh computer, using programs written primarily in MATLAB™.

PEMI MODEL VERIFICATION

The objective of the tests was to confirm that PEMI hardware and software were working as designed in preparation for the UXO response measurements. The model verification field tests were conducted using aluminum ring targets whose shape was a close approximation to the thin loop used in the target model.

Three types of targets were ultimately used in the field tests: thin aluminum rings, aluminum and steel cylinders (pipe sections), and UXOs (all UXOs used in this study are ferromagnetic). Table 1 presents the physical dimensions of the targets. In this paper, the dimension label of a UXO (e.g. 80 mm UXO) refers to its diameter, but the dimension label of a ring or a cylinder refers to its length along its axis of symmetry.

Target	Length (cm)	OD (cm)
2.5 cm Al ring	2.5	46.5
5 cm Al ring	5.0	49.9
100 cm Al cylinder	100	11.0
100 cm Fe cylinder	100	11.0
80 mm UXO	31	8.0
122 mm UXO	53	12.2
155 mm UXO	66	15.5

Table 1. Partial list of targets used in PEMI tests.

The fabricated 2.5 and 5 cm aluminum rings are 3.5 cm thick and almost 50 cm in diameter. The rings were selected to have time constants close to those of the UXO targets; $\tau_{2.5\ cm} = 9$ ms, and $\tau_{5\ cm} = 25$ ms.

The targets were suspended above the ground by a nonconducting structure depicted in Figure 5. The uprights and cross member were made of PVC pipe. The sensor rails were made of standard lumber 4x4s, routed with a groove which guided pins fixed to the underside of the sensor base. The beams were aligned, leveled, and then marked at all station locations. Station spacing was varied along the profile to provide better resolution near the target; the spacing varied from 25 cm to 1 m.

For convenience in positioning targets, measurements of UXO responses were all made in air; fortunately, soil conductivity is negligible at PEMI frequencies. A burial test was performed and confirmed that the host earth has no appreciable effect on PEMI responses. However, there was clutter in the soil of the test site (which was chosen before PEMI sensors were available) and the site response had to be measured in the absence of any above-ground conductors so that accurate UXO responses could later be obtained. To compensate for the clutter, the background response was simply subtracted from the total (UXO + background) measured response; space limitations prevent

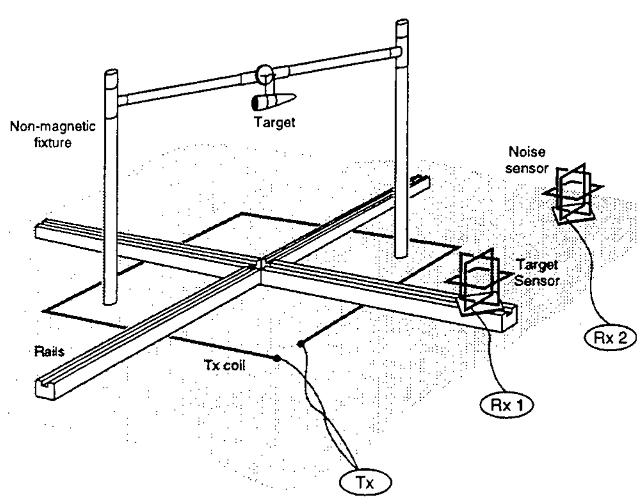

Figure 5. Test fixture used in making in-air measurements of UXO PEMI responses.

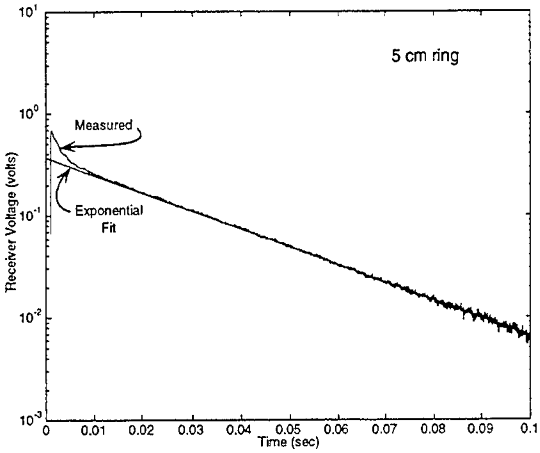

Figure 6a. Time response of the 5 cm aluminum ring and the best fit exponential decay with $\tau = 25$ ms.

further elaboration of that procedure here.

An example of a measured receiver voltage time series is shown in Figure 6a. The target is the 5 cm aluminum thin ring placed at a height of 2 m above the coordinate system origin, located at ground level at the intersection of the sensor rails. The distance ("depth") to the receiver placed at ($x = 0$, $y = 0$) was about 1.5 meters. For the simple ring target, the intermediate stage is very short compared to the target time constant. The late stage, visible during the time that the response appears as a straight line on the semilogarithmic plot, is clearly identifiable at times longer than about 10 ms. A fit of the data by a single exponential function produces a decay time constant of about 25 ms.

The spatial response of the test targets is also very well fit by the thin loop model. A typical 3-component response is presented in Figure 6b. Target geometrical parameters obtained from data inversion for the 2.5 and 5 cm aluminum rings compare favorably with their true values, verifying the validity of the PEMI forward models and

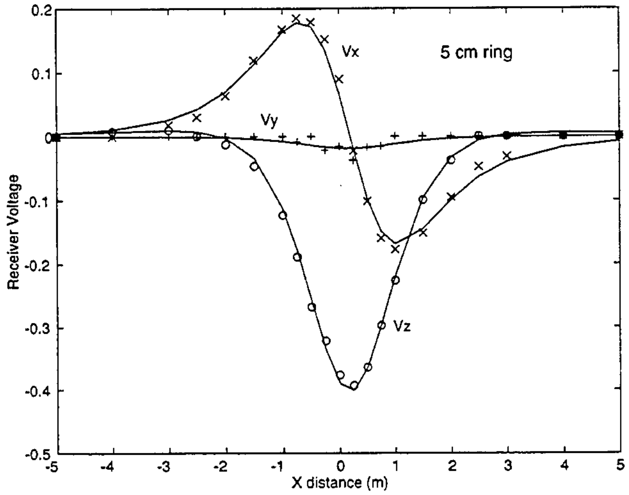

Figure 6b. Three component spatial response of 5 cm ring and the thin loop model fit.

Target		5 cm Ring	5 cm Ring	5 cm Ring	2.5 cm Ring
x (m)	Actual	0.2	0	0.9	-0.1
	Fit	0.2	0	0.9	-0.1
y (m)	Actual	-0.03	-0.05	0.9	0.1
	Fit	-0.1	0	0.9	-0.1
z (m)	Actual	-2.0	-1.9	-2.0	-1.4
	Fit	-2.2	-1.9	-2.0	-1.4
Tilt (deg.)	Actual	0	33	30	1
	Fit	10	33	27	9
Bearing (deg.)	Actual	†	0	45	†
	Fit		4	40	
Radius (cm)	Actual	23	23	23	21
	Fit	24	24	24	23

Table 2. Comparison between actual (as measured by hand) and DLS fit ring target geometrical parameters. †For small target tilt angles the bearing becomes insignificant and is not included in the table.

data inversion algorithm. The comparisons are summarized in Table 2. Due to the high SNR in these cases, background clutter removal is not necessary.

UXO RESPONSE MEASUREMENTS

Tests of inert UXO samples had one main objective: to determine whether the PEMI method could provide enough classification information to allow discrimination between clutter and UXO, and between different types of UXO. To this end, PEMI responses (both spatial and temporal) of 3 types of UXO (80, 122 and 155 mm) were measured and fit to the thin ring model. Specifically, late stage time constants were estimated and fits of spatial responses were performed using the thin loop model for several UXO sizes.

Temporal response

In general, the signal-to-noise ratio for the UXO measurements is not as good as it is for the 2.5 and 5 cm

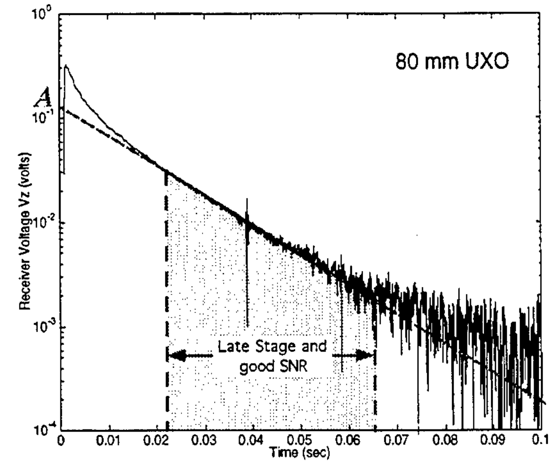

Figure 7. PEMI response of an 80 mm shell and the exponential fit obtained in the time window bounded by the onset of the late stage and reaching the noise floor.

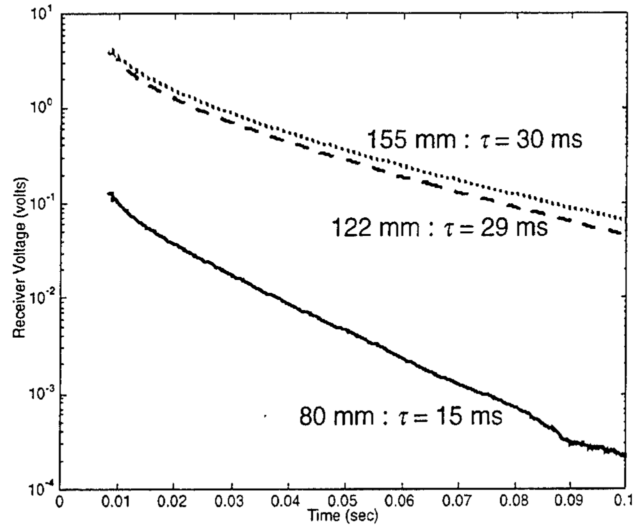

Figure 8. PEMI time series and estimated late stage time constants for the three types of UXO examined: 155 mm (dotted), 122 mm (dashed), 80 mm (solid).

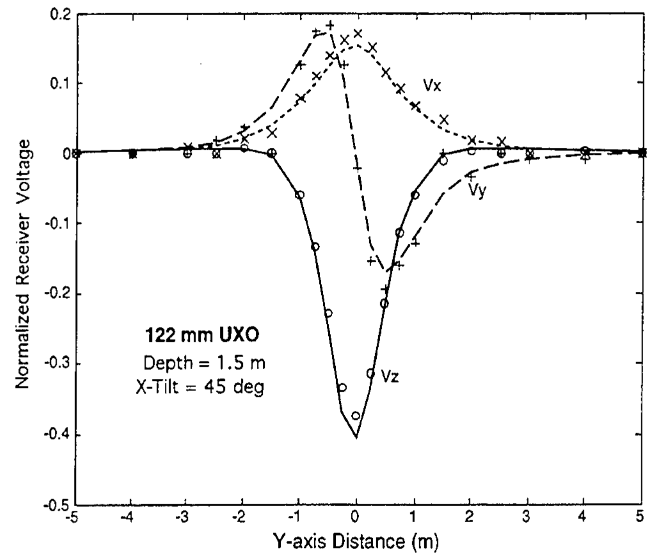

Figure 9. PEMI spatial response of a 122 mm shell and the thin ring model fit to the data. The data was collected along the Y-axis, and the target was tilted from the vertical by 45° in the XZ plane.

test rings. Longer data collection times (i.e. more pulses per station) and various forms of filtering (to reduce power line and natural ambient electromagnetic noise) were used to improve the SNR. Furthermore, to obtain good estimates of the UXO responses it became necessary to remove the influence of clutter buried in the vicinity of the test zone. Figure 7 presents a typical UXO response and illustrates the tradeoff between onset of the late stage and poor SNR in fitting a single exponential decay to the data.

Figure 8 presents PEMI time series for the 80, 122 and 155 mm UXOs after smoothing and background noise removal. The time constants were obtained by DLS fitting over an appropriate time interval. The length of the total recording time (100 ms), which was selected as the "off" time in the PEMI waveform of Figure 2 for most of the measurements in this project, was perhaps a bit shorter than it should have been for the larger shells. The signal level is still well above the noise at 100 ms and the response of a complex shape commonly reaches the late stage only after about $t = 2\tau$ or 3τ. The late stage time constants for the three shells are different, but not different enough to reliably discriminate between the 122 mm and the 155 mm shells. Nevertheless, PEMI data from this small sample of UXO shapes indicates that classification by late stage decay is likely to provide very useful information to discriminate between classes of UXOs and ordnance fragments.

The results of DLS fits of UXO spatial responses to the thin loop model were generally very good, as long as the distance between the UXO and the receiver was greater than the UXO length; otherwise, the elongated aspect of the UXO had measurable effects on the secondary field shape not taken into account by the simple loop model.

Figure 9 presents one typical example of a model fit to the response from a 122 mm shell. As described earlier, the values plotted as a function of space are the amplitudes of the exponential fits to the time series data at each station. The amplitudes represent the late stage response evaluated at time $t = 0$. Some of the ring parameters obtained as a result of the fit must be interpreted as *effective* values: inductance, resistance, and ring radius are not as directly useful as are ring position and orientation.

EOD TEST RANGE RESULTS

The NAVEODTECHDIV test range, known as the "magnetometer test range", is a plot of land on the base in which several specimens of inert ordnance were buried some 15 years ago. These inert UXO serve as realistic targets for testing various methods of detection and characterization. Three test sites, approximately square and 10 meters on a side, were selected and marked by EOD prior to the arrival of the PEMI field crew. The purpose of the test was to further examine the performance of the testbed PEMI system using buried inert UXO. No information regarding the specific locations or types of ordnance in the selected sites was available prior to the survey, though the general class of ordnance expected in the sites ranges from 60 mm shells to 2000 lb bombs. Other objects, conductive and/or ferromagnetic, may also be present.

Test procedure

The approach to surveying each site was to first lay out a grid using stakes and string on a 1 meter interval and place the 5x5 meter transmitter loop in the center of the grid. This grid was used to position the sensor in the horizontal directions. The height of the sensor coils was determined using a water level. The level consisted of a reservoir attached to the PEMI sensor platform out from which a water filled tube was extended to a meter stick fixed to a vertical post. The level in the reservoir was

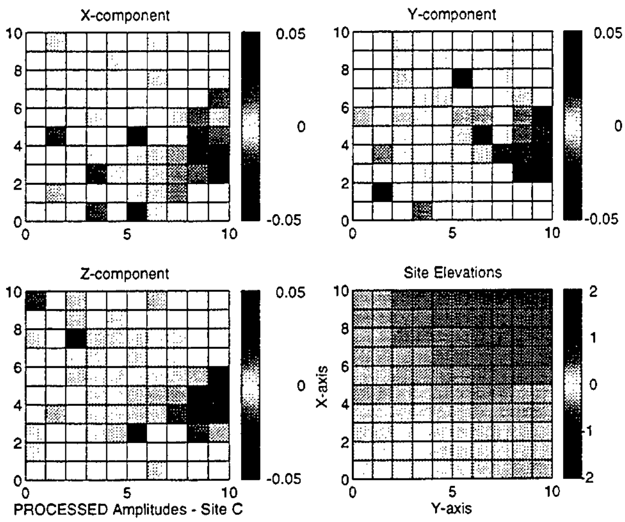

Figure 10. Site C - Amplitudes obtained from the DLS inversion of the time series data at each station. Note the presence of a target (C1) near (3,9); other targets are difficult to separate from clutter without "filtering" by time constant.

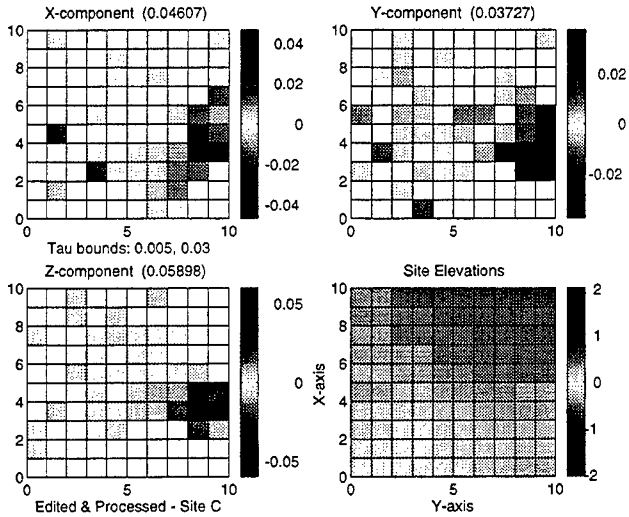

Figure 11. Site C - Amplitudes filtered using time constant bounds of 5 ms < τ < 30 ms. Target C1 is clearly visible in the Z-component data; X- and Y-components indicate other targets as well. From the detailed survey described below, it is known that target C2 is located near (3,1), and has a time constant of about 4 ms.

assumed to be fixed with respect to the PEMI sensor and when at rest was at the same height as the water level on the meter stick, thus allowing a simple reading of the sensor's elevation. For each station, the sensor's coordinates were entered by hand into the computer. In a practical field system, an automated locator would keep track of the sensor's position and orientation obviating the need for a detailed comprehensive grid and manual entry of position data.

Each site was first surveyed by gradient magnetometer (by Alliant Techsystems) and PEMI, making measurements every meter (i.e. at every string intersection). The PEMI preliminary area survey was intended to be used as a guide for locating finer profiles over targets of interest, but equipment problems prevented processing of the PEMI data while in the field. Instead, the results of the magnetometer survey directed the acquisition of detailed PEMI data. It turned out in post-processing that the PEMI area survey detected all of the targets seen in the magnetometer survey and more; discrimination was possible using the measured decay constants.

Once targets of interest were identified and approximately located using the magnetometer, two or three profiles centered over the expected target location were surveyed with PEMI using a 50 cm spacing between stations. Results of the survey are presented and discussed in detail for one of the sites, and summarized for the other two.

Results for Site C

Site C had the most elevation change and roughness across the area. Both the magnetometer and PEMI methods indicate a distinct anomaly near (3,9); this target is named C1. A few other minor regions of higher than background response also appear. One of these is a target (C2) detected by the magnetometer and also seen in the preliminary PEMI survey. Located near (3,1) conductor C2 is found to have a rather short time constant of approximately 4 ms.

The decay amplitudes from the prliminary survey for site C are presented in Figure 10. Though the plot appears noisy, a target near (3,9) definitely stands out as an anomaly expressed over several stations (target C1). Using a discrimination filter which sets to zero any amplitude with associated τ outside specified time constant bounds, here selected to be between 5 and 30 ms, and then rescaling the data to fully emphasize what is left after filtering produces the plots in Figure 11. The clutter spikes are gone, and the target response is clearly visible.

Target C1 was surveyed with profiles $y=8$, $y=9$, and $x=3.5$. For maximum signal, a small (1.25 meter) transmitter loop was used, with the loop centered at (3.5, 9). The amplitude weighted average estimate for the time constant is 8.1 ms, and the model fit to the spatial response is plotted in Figure 12 for one of the profiles (the fit is obtained using data from all profiles simultaneously).

	τ(ms)	X (m)	Y (m)	Z (m)	θ	φ	r_{eff}(m)
A	18.5	3.62	6.53	1.43	25	-82	0.23
B	21	2.06	7.26	1.01	29	-46	0.09
C1	8.1	3.30	8.51	0.21	84	89	0.10
C2	3.8	3.59	0.76	0.32	55	0	0.09

Table 3. Summary of target parameters for each of the targets found in the EOD test sites.

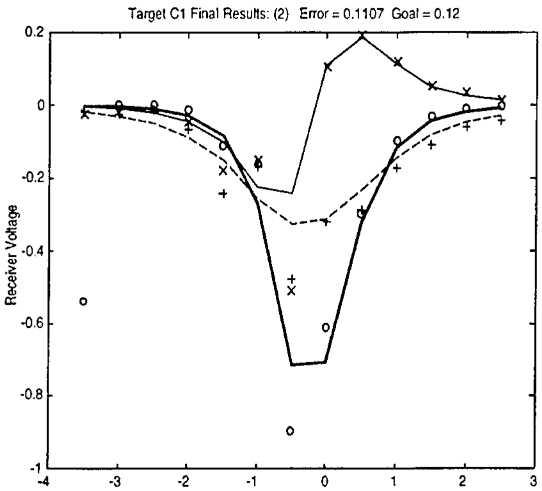

Figure 12. Profile data for target C1, from the profile y=9. The inversion is not affected by the outlying z-component data point at (-3.5, -.55) because it corresponds to a time constant outside a 30% interval around the average time constant of the target.

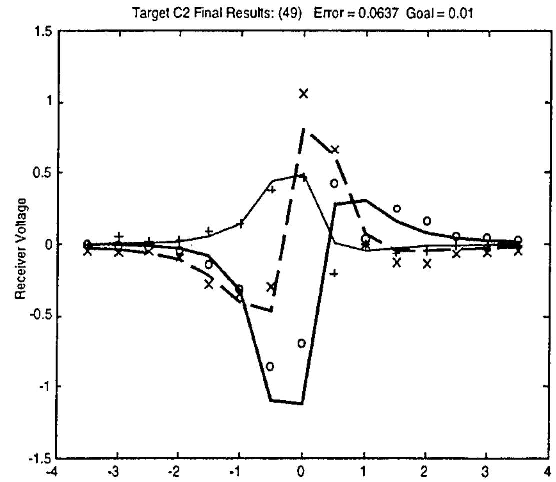

Figure 13. Profile data and fit for target C2, ($y = 0$).

Target C2 was surveyed with profiles $y = 0$, $y = 1$, and $x = 3.5$. For maximum signal, the small (1.25 meter) transmitter loop configuration was again used, with the loop centered at (3.5, 0.5). The amplitude weighted average estimate for the time constant is 3.8 ms. The spatial response model fit results (for the inversion of all three data profiles simultaneously) are illustrated in Figure 13 which presents the plot for one of the profiles ($y = 0$) for clarity.

SUMMARY: FY95 PEMI PROGRAM RESULTS

This project sought to evaluate the PEMI method for UXO detection and discrimination. To classify targets, the PEMI method uses the different decay rates of electric currents induced in conductors of different shapes and sizes by a pulsed magnetic field. Analytical models for magnetic fields and induced currents have been developed and validated using an experimental PEMI testbed. Typical accuracy of test target position and orientation estimates are better than 10 cm in depth, 5 cm in horizontal location, 5 degrees in tilt (polar angle), and about 10 degrees in bearing for common detection ranges of up to 5 meters.

Noise cancellation techniques are important components of practical field systems and several approaches were explored including low pass and notch filtering, averaging over many pulses, and using a remote set of sensor coils to measure coherent ambient noise for removal from the total target sensor signal.

PEMI responses from three inert UXO samples (80, 122, and 155 mm shells) were extensively measured. The ring target model is shown to do a good job of parameterizing the UXO response in many cases. The late stage time constants for the UXO samples are 14, 29, and 30 ms, respectively. The two large shells have very similar time constants and are not readily differentiable using late stage time constant information alone.

A second phase of field tests was held at the NAVEODTECHDIV test range in order to demonstrate the PEMI method in a "blind" survey of three 10 meter by 10 meter sites. Each site was given a preliminary survey by PEMI and magnetometer sensors, then detailed profiles were performed using the PEMI sensor over anomalous areas. Targets were detected, located and characterized in each site with good accuracy.

The results of the program confirm that the PEMI method is a very promising sensor technology for detection of buried UXO, and most importantly for discrimination between clutter and UXO.

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MULTI-SENSOR TOWED ARRAY DETECTION SYSTEM (*MTADS*)
AN AUTOMATED HIGH-EFFICIENCY SURVEY SYSTEM FOR CHARACTERIZATION OF ORDNANCE AND EXPLOSIVE WASTE (OEW) SITES

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ABSTRACT

The Naval Research Laboratory is developing a Multi-sensor Towed Array Detection System (*MTADS*) with support from the DOD Environmental Security Technology Certification Program (ESTCP). In this effort we seek to extend and refine ordnance detection technology to more efficiently characterize OEW sites, to include nonferrous and small ordnance items, to distinguish ordnance from clutter, and to analyze clustered targets as individual targets within complex target fields. Both magnetic and electromagnetic sensors are employed in arrays towed by a low magnetic signature vehicle. Survey guidance and navigation, based upon DGPS/RTK technology, is supplemented by dead reckoning navigation aids. Workstations are used for data processing and analysis. Data processing steps merge and time correlate all data streams, carry out data quality analyses and conditioning and display data as site maps and images. Data analysis tools are used to spatially process interactively selected targets determining position, size, depth, orientation and inclination. Target information from magnetometers, gradiometers and electromagnetic sensors is correlated and target tables, output maps and images are created using graphics tools. Electronic output files are created for use with the survey vehicle to waypoint targets for remediation.

INTRODUCTION

The Chemistry Division of the Naval Research Laboratory, with support from the Environmental Security Technology Certification Program (ESTCP) [Marqusee, 1996] is developing an automated towed-array ordnance detection system for site characterization. The product of this advanced development technology demonstration program is a field prototype instrument suitable for commercialization or use at DOD ranges or in the public sector. The *MTADS* program follows ten years of research and exploratory and advanced development work that produced two preprototype towed-array systems of increasing sophistication. These systems were tested and demonstrated at numerous field sites including both ordnance sites [McDonald and Robertson, 1994] and Hazardous, Toxic and Radioactive Waste (HTRW) landfills [McDonald and Cochran, 1992], [McDonald, Robertson and Cochran, 1995] and [McDonald and Robertson, 1995]. The recent technology demonstrations at the Jefferson Proving Ground make it plain that no single sensor, even deployed in closely spaced arrays and aided by automated navigation and sophisticated data analysis systems, can be expected to detect all ordnance at complex ranges while effectively discriminating against false targets and clutter. [----, SFIM, 1994], [----, SFIM, 1995]

An increasing number of Department of Defense ranges are being decommissioned and much of this property will be returned to civilian use under the BRAC and FUDS programs. This transition requires that very strict standards of OEW detection and good quality assurance practices be followed in site characterization and remediation to assure the public safety. Because of the very high costs of remediation of heavily contaminated ranges it is likely that many areas will be prohibitively expensive to clean. Because the majority of remediation costs are associated with digging targets it is imperative to minimize the fraction of false targets identified in the site characterization process. These opposing drivers place an even more demanding requirement on UXO detection technologies that they detect all OEW targets while driving down the number of falsely identified ordnance targets.

To address these goals the *MTADS* program has chosen multiple sensor types to provide both sensitivity and discrimination. Array designs and deployment strategies also play an important part in developing an efficient characterization strategy. The ultimate ability to both accurately locate and identify ordnance and to discriminate against non-ordnance must rely on sophisticated data processing and data analysis capabilities. For this reason the *MTADS* demonstration program is developing a completely new data analysis system relying on advancements in

computational speed and graphics analysis capabilities, the implementation of more sophisticated magnetic physics models and the correlation of both magnetic and electromagnetic data. We have updated the DGPS navigation hardware and software, integrated dead reckoning navigation aids, and ruggedized field hardware in areas that were recognized as vulnerable in our earlier development programs. This paper addresses the major development tasks in this program and describes the field demonstrations that will test the system.

THE FIELD PLATFORMS

The field survey equipment includes the navigation system, the sensor platform that accommodates the sensor arrays, the reference sensor, and the tow vehicle. The tow vehicle houses the data acquisition computer, the survey guidance computer, the roving navigation hardware and the power components for all field systems.

The Tow Vehicle

The *MTADS* tow vehicle is a third generation development. The primary requirements for the vehicle include a low magnetic self-signature, a rugged mechanical design requiring low maintenance, good ground clearance and maneuverability for operation in difficult terrain, a light footprint to minimize weight on the ground, support power to operate all sensors, guidance systems and the data acquisition system for two uninterrupted four hour survey sessions in an eight hour day. Environmental control is required to support summer and winter operations of all hardware and software components. Finally, the system must be ergonomically designed to allow the driver to monitor and control all the data streams, the data acquisition computer, and the vehicle survey guidance computer while driving the vehicle continuously for several hour stretches.

The *MTADS* tow vehicle, shown in Figure 1, is manufactured by Chenowth Racing Vehicles. The concept is based upon a Baja dune buggy and also draws heavily on similar vehicles they manufactured for the military which were used in Desert Storm operations. Except for some engine and transmission components, all ferrous materials have been replaced by composites and nonmagnetic alloys. The design specification calls for a vehicle self-signature of <5 nTesla at the magnetometer sensor positions. Studies we carried out using the *MTADS* charging system and test rigs that show operation of the vehicle alternator creates about a 30 nTesla differential field at the magnetometer positions north and south of the vehicle. [Glenn, 1995, 1996] We have installed battery capacity in the MTADS vehicle to operate all systems for eight hours to allow the charging system to be disabled during data acquisition. Fenders have been added to reduce mud splatter and an air conditioner to allow for temperature and dust control to protect the electronics.

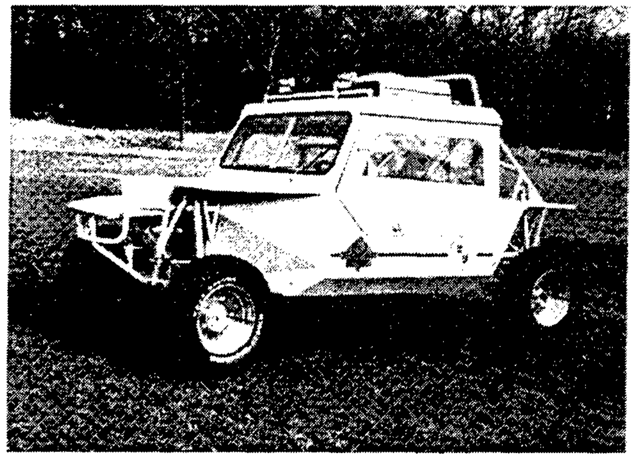

Figure 1. Photograph of the *MTADS* tow vehicle manufactured by Chenowth Racing Vehicles.

The Passive Sensor Platform

The platform to support the magnetometer and gradiometer arrays is a four-wheeled trailer connected to the tow vehicle by an 10 foot tow bar. The design allows the trailer wheels to track in the tow vehicle foot print. The trailer and sensor boom both use gas shock absorber suspension. All trailer and tow bar components are nonferrous alloys and composite materials. The sensor boom is designed to accommodate eight full-field magnetometers either as an eight magnetometer array or as a four-over-four gradiometer array. Horizontal sensor spacings can be either 0.25 or 0.5 meters. The sensor boom can be set for 25, 40 or 55 cm sensor ground clearance. When the sensors are deployed as gradiometers the vertical sensor separation is adjustable between 25 and 50 cm.

The Active Sensor Platform

The *MTADS* sensor platform designs do not allow simultaneous acquisition of data from active and passive sensors. Our studies show the simultaneous deployment of active and passive sensors adversely affects the quality of each data set. [McDonald and Robertson, 1996a] The passive platform takes advantage of several years of design and field test work. It has a carefully designed suspension system to minimize shock and vibration noise and makes extensive use of aluminum alloys. The active sensors are not particularly shock sensitive but cannot tolerate use of any metal components. Therefore, a simpler, all composite, sensor trailer was designed for the active sensor array.

Three modified EM-61 sensors form the active array. The transmit coils are deployed in a 0.5 meter overlapping horizontal spacing. The synchronized transmit and receive coils are deployed 40 cm above the ground. The upper sensor coils are 50 cm above the transmit coils.

NAVIGATION

The primary navigation is based upon the Differential Global Positioning System (DGPS). Our Trimble 4000SSE units have been upgraded to 4000SSI systems. One unit is deployed at a fixed, first-order, site with absolute coordinates known to <3 cm. The roving unit is located in the tow vehicle and the roving antenna is located above the center of the sensor array. The upgraded DGPS/RTK systems compute position coordinates "on the fly" and provide real time position read outs to the data acquisition computer (DAQ) at 1 Hz with centimeter accuracy. An electronic compass and pitch, roll, and yaw sensors on the sensor platform provide additional position information to the DAQ at 20 Hz. Finally, two tick wheel sensors on the right and left wheels provide down-the-track information to the DAQ. The attitude, compass and tick wheel sensors are designed to provide dead reckoning navigation with a position accuracy of <0.5 meters for a period of 20 seconds if initialization is lost by the DGPS.

DATA ACQUISITION/SURVEY GUIDANCE

Data acquisition and survey guidance are handled by two Pentium 100 MHZ field ruggedized computers in the survey vehicle. The data acquisition computer accepts navigation information from the Trimble DGPS and the position and attitude sensors simultaneously recording magnetic or electromagnetic sensor data at their characteristic data rates. All files are time stamped with the Trimble satellite clock timing pulses. The data acquisition computer has sufficient data storage capacity for eight hours of operation.

The survey guidance computer also receives the DGPS and other position sensor inputs. The survey site is displayed on a touch screen monitor in front of the driver along with the survey plan. The real time vehicle position and survey track guidance information is also displayed. Prior survey coverage is shown in color 1, current DGPS/RTK survey tracking is shown in color 2. If RTK solutions are lost, the DGPS track is shown in color 3. If DGPS navigation is lost, the dead reckoning progress is shown in color 4. Missed areas within the survey site are highlighted for the operator. Some additional sensor status and power information is also available on the touch screen. The survey guidance computer also directs the vehicle during target acquisition and way pointing following target analysis.

ORDNANCE SENSORS

Prior to specifying the sensors for the *MTADS* arrays, NRL conducted a sensor performance evaluation at The Magnetic Test range at Ft. Devens, MA. Geometrics 822G full field sensors were evaluated both as magnetometer and gradiometer arrays deployed in a variety of configurations. A Schoenstedt GA52Cx fluxgate gradiometer array was evaluated, as was an array of Geonics EM-61 active sensors. Geometrics Model 856 proton procession sensors were evaluated in a gridded survey and a Scintrex "Smart Mag" sensor was demonstrated in a walking line survey. The Test Range contains 36 ordnance and ordnance simulants ranging from 155mm projectiles to 500 lb bombs buried at depths up to 17.5 feet. Twenty four small targets, pipe segments 1" and 2" in diameter ranging from 3" to 12" in length, were emplaced. Additionally, eight cold-rolled 55 gallon steel barrels are buried at depths from 4.5' to 16.5' and one 55 gallon Al drum is buried at 4.5'. The performance of each of these sensor systems was extensively and critically evaluated. The results were presented by [McDonald and Robertson, 1996a] and were used to evaluate various sensor deployment strategies and to formulate survey designs. This information is presented in [McDonald and Robertson, 1996b].

Passive Sensors

Magnetometer specifications were determined based upon the results of these tests and an improved sensor, the Geometrics Model 822ROV was chosen for use both as an eight sensor magnetometer array and as a four-over-four vertical gradiometer array. Figure 3 shows a magnetic anomaly image of the two acre Ft. Devens range using the magnetometers as a vertical gradiometer array. Seven of the 55 gallon drums are apparent in a row along the left side of the image, the deepest barrel is barely discernable on this scale in the lower left corner of the image. Parallel to the line of drums is the line of 1" and 2" diameter pipe segments. The 155 mm targets and the 250 lb bombs are evident in the image. The larger (and deeper) bombs are less obvious in the gradiometer display.

Figure 4 shows a 50 X 50 meter pan window magnetic anomaly image of the southwest corner of the site taken with the eight sensor array deployed as full field magnetometers. Several pipe segments, barrels and bombs are noted in the image. Relatively shallow, tightly clustered, targets and shallow small targets are better detected and analyzed using gradiometry. The full-field magnetometer array more sensitively detects the larger deepest targets. The Geometrics Model 822ROV sensors were chosen for the passive magnetometer and gradiometer arrays for *MTADS*.

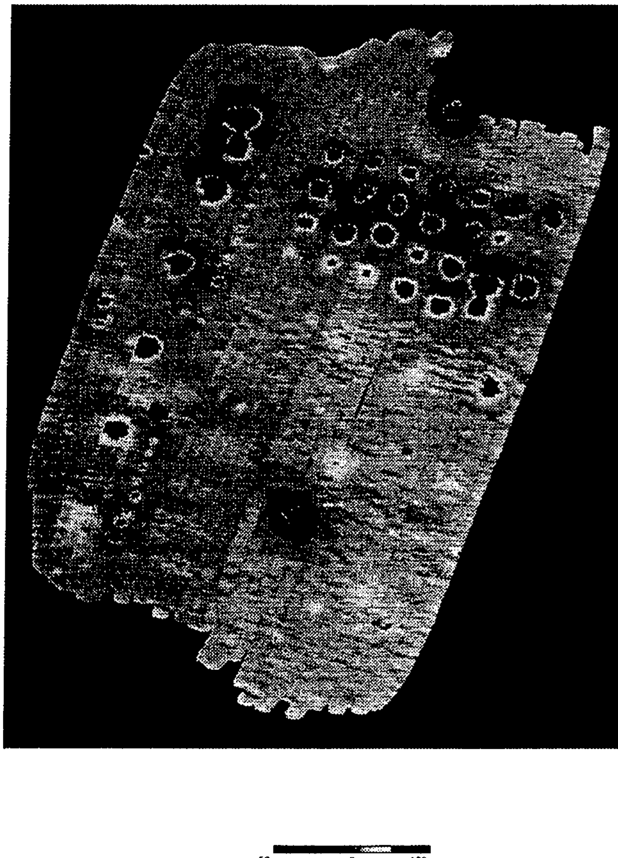

Figure 2. Magnetic Anomaly Image of the Ft. Devens site. Geometrics Model 822G sensors were used in a 4 over 4 vertical gradiometer array at 18 and 36 inches.

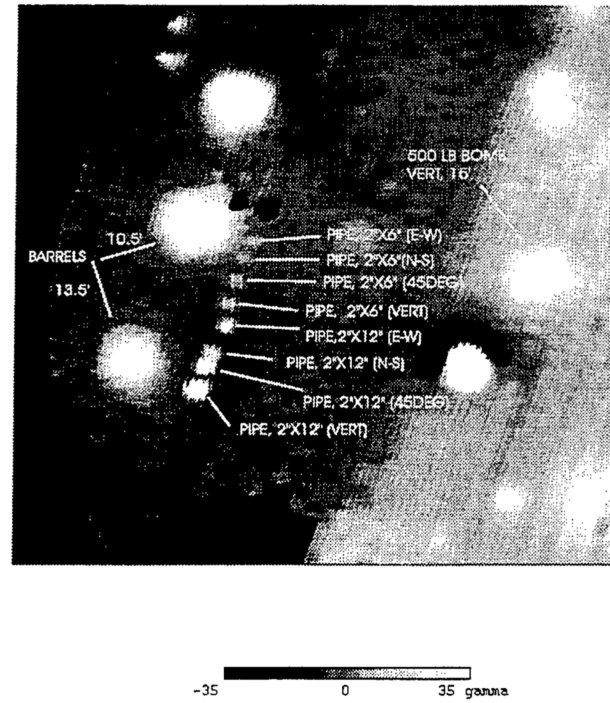

Figure 4. A 50 X 50 meter pan window magnetic anomaly image of the southwest section of the range. Geometrics Model 822G sensors were used as an eight sensor array of full field magnetometers.

The new Model 822G sensors allow a choice of data rates up to 80 Hz. There are tradeoffs among sensor precision, effective time constant and sampling rate. The studies at Ft. Devens clearly demonstrated that high density data sets are required to confidently detect and analyze the smallest targets. Therefore, sensor mounting provisions were made to allow horizontal array spacings as narrow as 0.25 meter. Data rates and spacings can be adjusted depending upon whether small near-surface targets must be detected. Strategies for survey planning are discussed in [McDonald and Robertson, 1996b].

Active Sensors

Geonics EM-61 pulsed induction electromagnetic sensors were chosen for use with the *MTADS*. The time domain sensor transmits a 3.35 msec pulse at 75 Hz from its 1 meter square transmit coil. This pulse induces a secondary field in nearby objects which radiates with an intensity and time decay profile that is dependent on the characteristics of the target. The EM-61 has one receive coil co-located with the transmit coil and a second receiver 40 cm above the lower receiver. The commercial instrument is configured to allow the user to discriminate against small near surface metallic clutter and to accentuate deeper objects such as buried tanks.

We conducted an experimental analysis of the system performance and compared it with theoretical models which we developed for various sized objects of different metals as a function of distance from the sensor. [Barrow, 1996] Figure 5 shows a comparison of the experimental signal measured from a 4.9" Fe sphere one meter below the coil during the 0.5 msec receive window used by the sensor. The dotted curves are the theoretical model using the conductivity and magnetic permeability values indicated. These models were applied to the Ft. Devens data set as shown in Figure 6. The diamonds indicate the ferrous target distribution as a function of size and depth. The theoretical limits of detection for Fe and Al are shown as the cross hatched curves. The filled symbols indicate targets that were experimentally detected in the analysis. All targets falling on or above the predicted limits of detection were easily

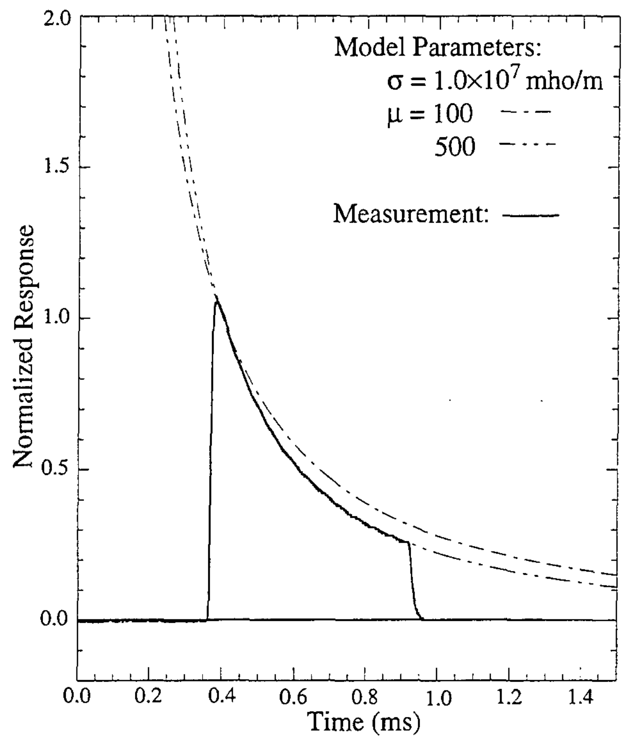

Figure 4. Experimental and modeling comparison of the Geonics EM-61 sensor performance measuring a ferrous object.

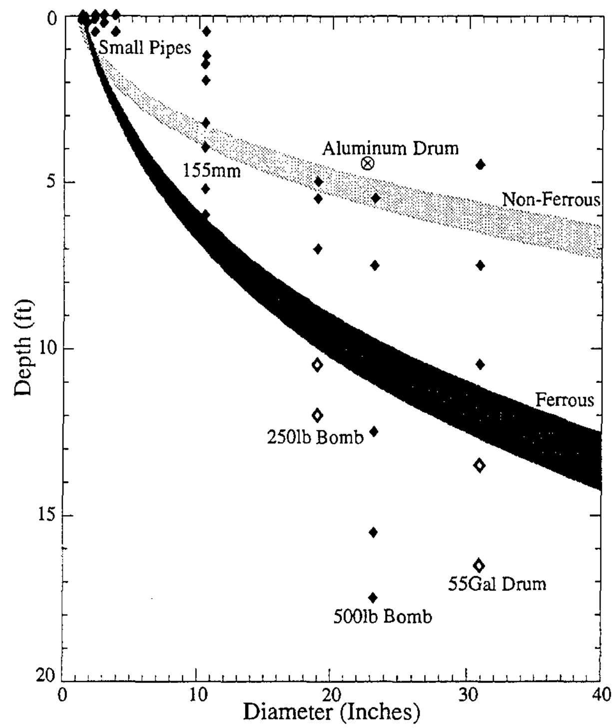

Figure 5. Theoretical limits of detection of the Geonics EM-61 sensor based upon signal to noise considerations. The upper curve applies to Al and the lower curve to Fe objects. Objects at the Ft. Devens test range are plotted as discreet points.

identified. The analyst was able to identify the 500 lb bombs more efficiently than predicted by the model.

As a result of these studies we have purchased the EM-61 sensors for the *MTADS* customized to our specifications, changing the transmit repetition rate and intensity, changing the receive window in time and width and changing the level of amplification in the receivers. The transmit and receive coils of the three unit array are modified to operate synchronously. We expect all these modifications to significantly improve the operation of the active sensor array for both small targets and for large deep targets in UXO site characterization studies.

DATA PROCESSING AND ANALYSIS

Field data can be transferred for processing by several redundant mechanisms. Short surveys or short data files can be transferred by floppy disk. Longer files are written to "dat tape" by the data acquisition computer. Additionally, files can be transferred directly to a notebook computer by parallel-to-parallel port link. Files are down loaded to the data analysis computer for processing.

All data processing, data analysis, file and output table generation and standard graphic creation will be handled by the SGI Indigo workstations. One workstation is resident in the *MTADS* development lab, a second system will travel with the *MTADS* to for field studies and be located near the field site. The two workstations are identical and operate the same data analysis software. Field data can be transferred by modem or FTP network connection to the NRL computer, if required.

The first step in processing brings all the field data files together. Landmark and setup files are used to define the survey site. Navigation and position files are processed using DGPS/RTK, DGPS, Inertial Guidance and compass data, along with any necessary post processing and editing to create survey track files.

Magnetic and electromagnetic sensor data files are rationalized with reference sensor data, and normalized for sensor calibrations and offsets and vehicular/survey induced artifacts. At this point the data can be analyzed for peculiar

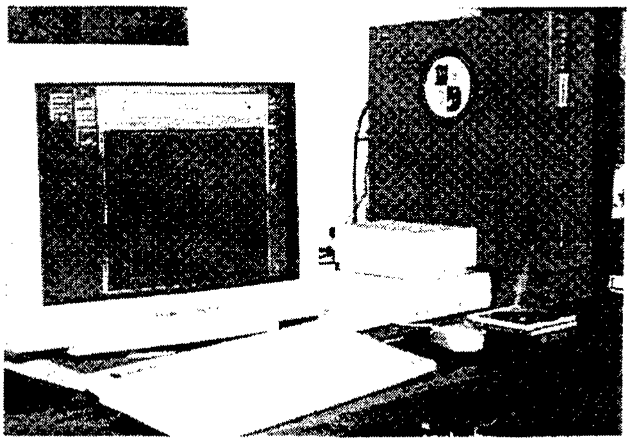

Figure 6. Data processing and analysis hardware for the *MTADS* system.

noise characteristics, sensor malfunctions, or other data artifacts created by the sensors or by cultural artifacts at the survey site. The analyst has options for data editing, filtering, or smoothing, as appropriate. The data are then mapped onto the survey track file either as discrete sensor data or mapped onto a grid and interpolated. All data processing to this point can be handled using default settings in the *MTADS* data processing program or the analyst can intervene using numerous menu options in the setup and pre-processing windows.

Target Analysis

Target analysis takes place at the workstation with the analyst interactively specifying and bounding targets for analysis. Magnetic or electromagnetic anomaly image maps are presented to the analyst (either as discrete or interpolated images). The analyst can zoom the image to a preferred scale, choose among gray scale, false color or highlighted presentations, and rescale to optimum intensity saturation limits for different target sizes and types. The analyst bounds a potential target with the computer mouse and the data analysis program analyzes all data within these bounds. An iterative multivarient analysis is carried out fitting the data to a model. The model for magnetic data is a point dipole model. The computer displays images of the data and the model fit, the target model parameters including position, depth, orientation and size (magnetic moment, spherical volume equivalent or equivalent ordnance caliber). Goodness of fit data are also presented to the analyst to aid his decision to accept the target, re-bound the target for analysis or to reject the target as non-ordnance.

Analysis proceeds in this manner until the survey characterization is complete. At this point target image plots, target maps and target tables are prepared by the computer. The analyst has the option of comparing or correlating data sets taken with other sensors (magnetometer, gradiometer or electromagnetic sensors). Output image or target plots can be formatted for incorporation into GIS databases, if such data bases exist, for a given site. Output graphics can be created at the workstation for the site manager or for survey reports or presentations. Laser printers and dye sublimation color printers are available for creation of high quality graphics.

TARGET LOCATION AND WAY POINTING

Following completion of the target analysis, the data analysis computer is used to create output files for the data acquisition and survey guidance DAQ computers. These files are loaded into the vehicle computers. The survey guidance computer, using the survey map, anomaly images, and target coordinates, directs the vehicle to the target coordinates. Software designed for this purpose, using the "traveling salesman algorithm" provides for the most efficient way pointing operation. Depending upon the site and the density of targets, the way pointing can be carried out using the vehicle alone or the vehicle connected by a long cable to a DGPS antenna that is carried by hand to the target coordinates under direction of the guidance computer. The latter process is much more efficient if there are many targets to mark.

MTADS/ESTCP DEMONSTRATIONS

MTADS system integration is taking place at the NRL Chesapeake Bay Division (CBD) field site. We have acquired numerous inert ordnance items to create a local test and demonstration site at CBD. This site will be used to complete the system assembly, shakedown and evaluation and initial demonstration.

Twentynine Palms Magnetic Test Range Demonstration

The Naval Explosives Ordnance Disposal Test Center (NEODTC) and NRL created an ordnance test range at the Marine Corps Air Ground Combat Center in Twentynine Palms, CA several years ago. A wide range of ordnance was buried at the range using careful survey control based upon a local grid. The ordnance positions and orientations are known (within the local grid) to an accuracy of 3-5 cm. NRL will demonstrate the *MTADS* system at this test range using a variety of sensor and array configurations. The range is relatively magnetically quiet geologically, but has a significant amount of clutter present from other operations that have taken place over the last several years. The system performance will be evaluated at this range following

analysis by *MTADS* personnel. The *MTADS* data files will also be independently analyzed in a blind test by Institute for Defense Analysis (IDA) scientists, following a short training course in the use of the *MTADS* data analysis system.

Jefferson Proving Ground Demonstration

The *MTADS* will be used in late 1996 to conduct a blind survey of one of the forty acre prepared ordnance ranges at Jefferson Proving Ground in Indiana. NRL will conduct the survey and data analysis. The results of the demonstration will be evaluated by IDA personnel against the truth tables that they have used to evaluate the system performance of other demonstrators at these sites.

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THE PHENOMENOLOGY OF DETECTING BURIED UXO

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ABSTRACT

The need for and difficulties associated with clearing land contaminated with unexploded ordnance (UXO) is attracting increased attention as a result of the base closure process and as a result of recent high profile clearance activities in built-up areas. The resulting increased emphasis on the detection of buried UXO has led to a number of initiatives based on sensing technolgoies used in other areas, such as environmental monitoring, geological research and prospecting, and military reconnaissance and surveillance. The targets, background, and operating conditions are very different for these applications than for the UXO clean-up arena. This paper presents an overview on the aspects of targets, background, and operating conditions that will limit detection capability of current and proposed approaches to the detection of buried UXO. The paper covers target signatures, signal propagation from the target to the sensor, system sensitivity, and background discrimination. The effects of target size, depth and orientation, geological character of the ground, available system sensitivity and the sources of background signals are discussed in some detail for ground-penetrating radars. Brief descriptions of the analysis issues for magnetometers, induction coils, and infrared sensors are also presented.

INTRODUCTION

The sensor technologies currently applied to the detection of unexploded ordnance (UXO) include magnetometers, induction coils, ground penetrating radars, infrared systems, visible imaging, and Light Detection and Ranging (LIDAR). A variety of acoustic, chemical, nuclear, and biological approaches are being studied for future application. This paper describes the critical parameters affecting detection performance of magnetometers, induction coils, GPRs and infrared imagers. These sensor parameters offer insight into the expected performance for a variety of the site conditions. The material presented here is taken from IDA Paper P-3114 (October 1995).

Magnetometer and electromagnetic sensors are fairly successful at detecting buried UXO. GPR and infrared sensors are not nearly as successful. The limited detection ability of the infrared system is not surprising since it is known to be better suited for detecting surface ordnance and recently disturbed earth. GPR on the other hand is designed for detecting buried objects. Currently there is a large gap between measured GPR performance and expectations. Thus, we focus on understanding the parameters that affect GPR performance.

DETECTION OF ORDNANCE BY MAGNETOMETERS

A magnetometer relies on the existence of a magnetic signature that is large compared to system noise and distinguishable from background magnetization for detecting buried ordnance. Two primary contributions that are of comparable magnitude determine the magnetic signature of the ordnance. First, since ordnance items are commonly fabricated with steel, which is ferromagnetic, the placement of buried ordnance in the earth's magnetic field contributes to the overall magnetic signature. In the vicinity of ferromagnetic ordnance, the local magnetic field will exhibit a slight deviation from the background geomagnetic field. The net field deviation near any ferromagnetic item from the background geomagnetic field is strongly dependent on the size, shape, orientation, magnetization, and location of the item. Table 1 shows characteristic vertical magnetic field and field gradient estimates, compared to the geomagnetic field.

Table 1. Characteristic Vertical Magnetic Field and Field Gradient Estimates

	Geomagnetic Field	*Magnetic Anomaly*	*76-mm Projectile at 2 m*
Magnetic Field (γ)*	50,000	1,000	5
Vertical Gradient (γ/m)	0.01	3	3.5

* 1 γ = 10^{-5} Oe, where the oersted is the cgs unit of magnetic field.

Second, ordnance items exhibit a weak remanent magnetization that is dependent on the manufacturing processes. (Remanent magnetization is defined as the magnetization that remains in a magnetic material after it has been magnetized to a level below saturation. See Jiles, 1991.) This magnetic field is "frozen into" the ordnance. During the manufacturing process, the earth's magnetic field causes a preferential orientation of the magnetic dipoles within the steel, leaving the object with a remanent

magnetization. The magnitude and orientation of the magnetization are influenced by metallurgical properties of the steel; for example, grain size, chemical composition, the physical orientation during formation, and the types of heavy machining required to produce the finished product all influence the remanent magnetization. In addition, firing and ground impact of the ordnance can alter its magnetization and thus its intrinsic magnetic signature. Although the remanent magnetic signature is generally smaller than the field perturbation caused by induced magnetization, there are instances where remanent magnetization dominates the magnetic signature of the ordnance.

CRITICAL PARAMETERS AFFECTING THE DETECTION OF ORDNANCE BY MAGNETOMETERS

The ability to detect magnetic ordnance items depends on many parameters. This technique is passive. The magnetic signature falls off as $1/r^3$, and is highly dependent on the orientation of the ordnance item in the background earth's magnetic field and also possibly on the remanent magnetization. In the absence of background magnetic clutter, the $1/r^3$ field dependence permits detection of magnetic ordnance to greater depths than can be attained using other currently fielded techniques. On the other hand, naturally occurring magnetic minerals, as well as magnetic manmade nonordnance items can cause magnetic signal clutter. It is realistic to expect background magnetic field anomalies of the same order of magnitude as anomalies expected from buried UXO.

Additional difficulty in detection of ordnance can occur because it is possible for the two magnetic components (remanent magnetism caused in manufacturing and variation in the geomagnetic field caused by the permeability of the ordnance item) to lie in an orientation which is unfavorable for detection, or even partially cancel, depending on the orientation of the ordnance's remanent magnetization relative to the geomagnetic field, and induced magnetization of the ordnance.

DETECTION OF ORDNANCE BY INDUCTION COILS

Induction coils can be used to detect the metal associated with most ordnance items. In an induction coil, a time-varying electric current in a transmitting coil produces a time-varying magnetic field. This fluctuating field will induce a voltage resulting in eddy currents in conductive material. For a pulsed IC system, when the transmitting field is turned off, the decay of the eddy current will, in turn, induce a voltage in a receiver coil. Because the induction system relies on induced currents, this system can be used to detect any conductive material and is not limited to ferrous metals. However, an induction coil will also be susceptible to false alarms arising from all nearby nonordnance items made of conducting materials. IC's are believed by some to be unsuitable for searching for electronically fused UXO since the induced current may trigger detonation.

Induction coils are generally pulsed with a repetition rate in the kHz range. The decay time of the induced current depends on the geometry, magnetic permeability, and conductivity of the medium in which the current is induced. Since the conductivity of most natural objects and even the most conductive soils is orders of magnitude below the conductivity of metal, time gating the receiver coil can exploit the difference in decay time between highly conductive manmade items and surrounding naturally occurring conductors in the soil.

CRITICAL PARAMETERS AFFECTING THE DETECTION OF ORDNANCE BY INDUCTION COILS

The transmitter coil of an induction system produces a magnetic field that falls off with the cube of the distance between the coil and the object of interest at large distances compared to the size of the coil. The field produced by the induced current in the conductor, which is the source of the voltage induced in the receiver coil, will fall off by the same $1/r^3$ relation to distance. In the far field limit, the signal in the receiver coil, therefore, will fall off as $1/r^6$, where r is the distance from the induction coil system to the buried item. So far we have neglected any signal loss due to attenuation of the electromagnetic field through the soil. Although this source of loss is an important consideration in the performance of GPRs (discussed below), at the frequencies typically used for inductive measurements, the effect of soil attenuation is expected to be small in comparison to the fall off of the field with distance in free space. For a relatively high conductivity of 0.1 mho/m and a 10-kHz frequency, the one-way attenuation is expected to be less than 20 percent at 3-m depth. The attenuation will be greater for higher frequencies and lower for lower frequencies. At sites with lower conductivity, the attenuation will be less at all frequencies.

DETECTION OF ORDNANCE BY GROUND-PENETRATING RADAR (GPR)

The sequence of events in radar detection of underground objects is as follows: First, a radar pulse, usually of very short duration, is emitted. If the antenna is not in electrical contact with the ground, the radar wave propagates through the air to the ground. At the air-ground interface some energy is reflected; the amount depends upon the angle of incidence, the wavelength, the dielectric constant of the medium, and the surface roughness. Some of the energy penetrates the ground. If the antenna is in electrical contact with the ground, there are minimal losses at the air-ground interface. The radar pulse propagates through the ground and is scattered as a result of changes in the dielectric constant. These can be continuous changes in the dielectric constant arising from differences in soil content, or boundary changes due to the presence of buried ordnance, benign man-made objects, rocks, or other inhomogeneities in the soil. The amount of backscattering depends upon the magnitude of the change in

dielectric constant, the size and shape of the object creating this change, and the radar wavelength.

While the pulse propagates, it is attenuated by the medium through which it is traveling. Significant energy is lost through this attenuation, which is a strong function of the frequency. In addition, differences in dielectric constant as a function of frequency spread the pulse in time. Specifically, the speed of light in a dielectric medium depends on the dielectric constant, which varies with frequency. Hence, radar waves of different frequencies have different velocities in the medium, and the wave spreads out.

The energy that is backscattered is collected by the antenna. For the simplest case, the antenna is in contact with the ground, transmitting an approximate plane wave into the ground. The time required for the return of the short pulse is used to determine the depth of the object. The resolution of this depth determination is approximately equal to half the pulse duration multiplied by the speed of light. Imagine an area of land divided horizontally into parcels the size of the antenna's beam spot on the ground and divided vertically into sections each with the depth of the range resolution. Detection of ordnance items with high probability and low false alarm rate requires that the returns from any of these "boxes" containing ordnance be large compared to the returns from "boxes" with no ordnance and compared to system noise.

In general, there is a trade-off between cross section and attenuation for the detection of any underground objects. The analysis presented later indicates that, for conditions at the JPG demonstration, soil attenuation was sufficiently great, even at frequencies of a few hundred MHz, that detection of ordnance items would be difficult, if not impossible, with GPR (U.S. Army Environmental Center, 1995; Altshuler, et al., 1995). Even for low frequency GPRs that have relatively good soil penetration, the scattering cross-section of ordnance objects will be low. For higher frequency GPRs, where the scattering cross-section of ordnance objects is high, the soil penetration will be poor because of a combination of high conductivity and soil moisture. Calculations and analyses are also presented below for soil conditions more favorable for GPR.

The airborne systems suffer additional losses due to reflection at the air-ground interface and greater stand-off range. Furthermore, for the side-looking airborne radars, as opposed to the down-looking surface radars, there are discrete clutter objects on the surface that appear in the same range gates as the buried target, and discrimination for all but the largest objects is effectively impossible.

CRITICAL FEATURES AFFECTING THE DETECTION OF ORDNANCE BY GPR

There are many parameters that affect the performance of radars in general and GPRs in particular. Understanding the results obtained by radars hinges on understanding the combined impacts of decreasing cross sections at long wavelength and the attenuation of the waves at short wavelength. The critical parameters, therefore, are the radar cross section and the attenuation through soil, both viewed as a function of frequency (or wavelength). Simple models for these parameters are presented below, and are used for quantitative estimates of detection ability in the next section.

A SIMPLE MODEL OF RADAR CROSS SECTIONS

Our calculations require a model for the radar cross section of a variety of objects over a wide range of frequencies. We will begin by considering the solution for scattering from a conducting sphere [see Fig. 1, taken from Crispon and Siegel, eds. (1968)] as a basis. The cross section in the long-wavelength Rayleigh region is proportional to the volume squared divided by the wavelength to the fourth power. In the short wavelength optical region, the cross section is defined by the presented area. In between, where the wavelength is on the order of 2 π times the radius of the sphere, the cross section shows resonance structure.

For the ordnance problem, we will approximate bombs and projectiles as cylinders, and mines as disks. For these shapes, there exist exact formulae for the Rayleigh and optical regions. To keep the analysis simple, we will use the Rayleigh cross section at low frequency, (evaluated using the free space wavelength) until it intersects the optical limit, and the optical value thereafter. This is illustrated by the dashed line on Fig. 1 for a sphere. Neglecting the resonance structure and the change in wavelength due to the dielectric constant of the ground will generally result in underestimation of the cross section. However, for cylinders and disks the presented cross section will depend on orientation as well and we will generally use the maximum cross section orientation for our calculations. Therefore, the errors generated by these approximations will tend to offset one another. We should note that these are the cross sections for perfect conductors of these shapes, an excellent approximation for metals. The approximation overestimates the cross sections of plastic mines, stones, or other objects with finite dielectric constant, typically by a factor of several. We ignore these effects in the following discussions. Table 2 gives the Rayleigh and optical cross sections for spheres, cylinders, and disks, and the value of the wavelength where they are equal, in terms of the wavelength λ, the volume V, the radius a, and, for the cylinder, the length L. See Crispon and Siegel, eds. (1968), for a more complete discussion.

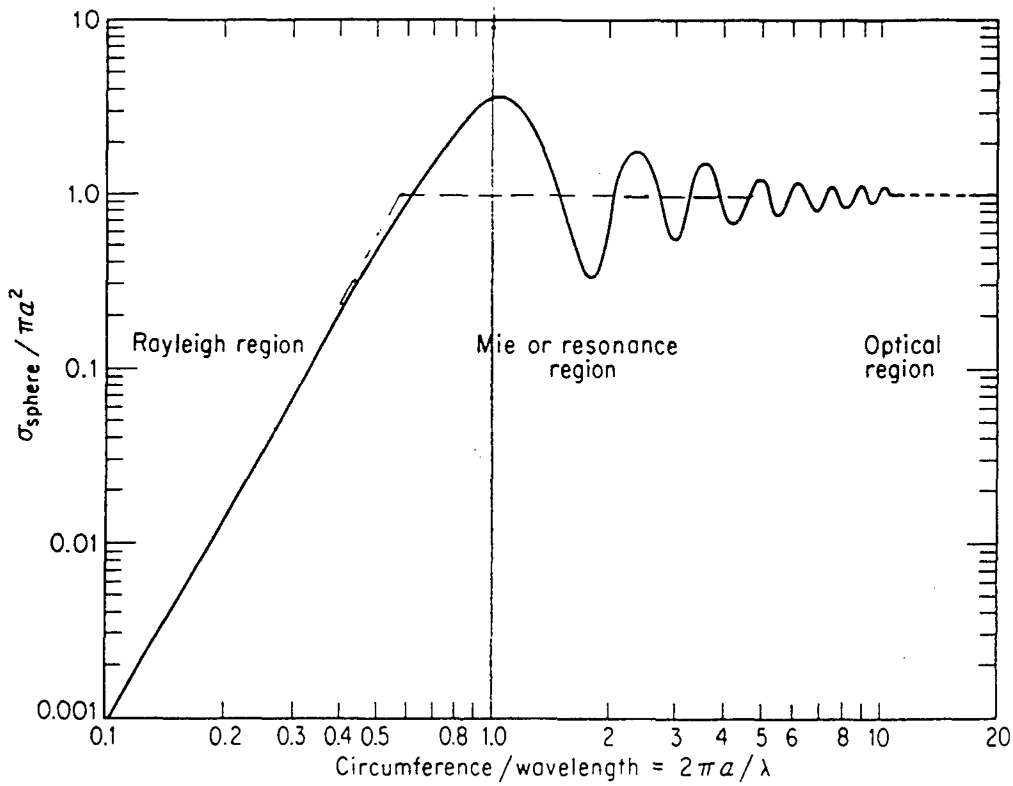

Figure 1. Radar Cross Section, σ, of the Sphere. a = radius; λ = wavelength.
(Source: Crispon and Siegel, 1968)

Table 2. Rayleigh and Optical Limit Cross Sections for Various Shapes

	Rayleigh Limit	*Optical Limit*	*Matching Wavelength*
Sphere	$81\pi^3 V^2(1/\lambda)^4$	πa^2	$\lambda = 3\,(2\pi a)$
Cylinder	$64\pi^3 V^2(1/\lambda)^4 F^2$	$La(2\pi L/\lambda)$ *	$\lambda = 4\pi a(\pi/2F^2)^{1/3}$
	$F = (1 + 4a/3\pi L[e^{-(3L/4a)}])$		
Thin Disk	$64\pi^3 a^2(a/\lambda)^4$ *	$\pi a^2(2\pi a/\lambda)^2$ *	$\lambda = 4a$

* Maximum cross-section orientation.

A SIMPLE MODEL OF RADAR ATTENUATION

Attenuation of radar waves is driven by two effects. The DC conductivity of the medium is the dominant effect at low frequency. At higher frequencies, the water content of the soil leads to resonance attenuation via the same phenomenon that enables a microwave oven to heat anything with water in it. These effects have been both measured and calculated. We present in Fig. 2 calculations for 15 percent water content and a variety of conductivities [Internal memorandum, M. Braunstein, IDA; also Davis and Amman (1989)].

DETECTABILITY OF MINES BY GPR

For small buried objects such as mines, effective detection will be limited by the ability to distinguish the mines from other small objects, which may be at a shallower depth. Figure 3 shows the two-way attenuation through 4.8 in. of soil. Also shown is the dependence of the free space cross section (in arbitrary units) of a 4.5-in. diameter disk as a function of frequency.

The problem with detectability is clear. At higher frequencies (>1,000 MHz), where the free space cross section is large, the attenuation will limit detection. At lower frequencies where the attenuation is low, the free space cross section of a mine-size object is vanishingly small. Another way of viewing this is in Fig. 4, where the free space cross section and the attenuated responses (the product of the free space cross section and the attenuation) are plotted as a function of frequency. We note that the response does not depend very much upon the conductivity.

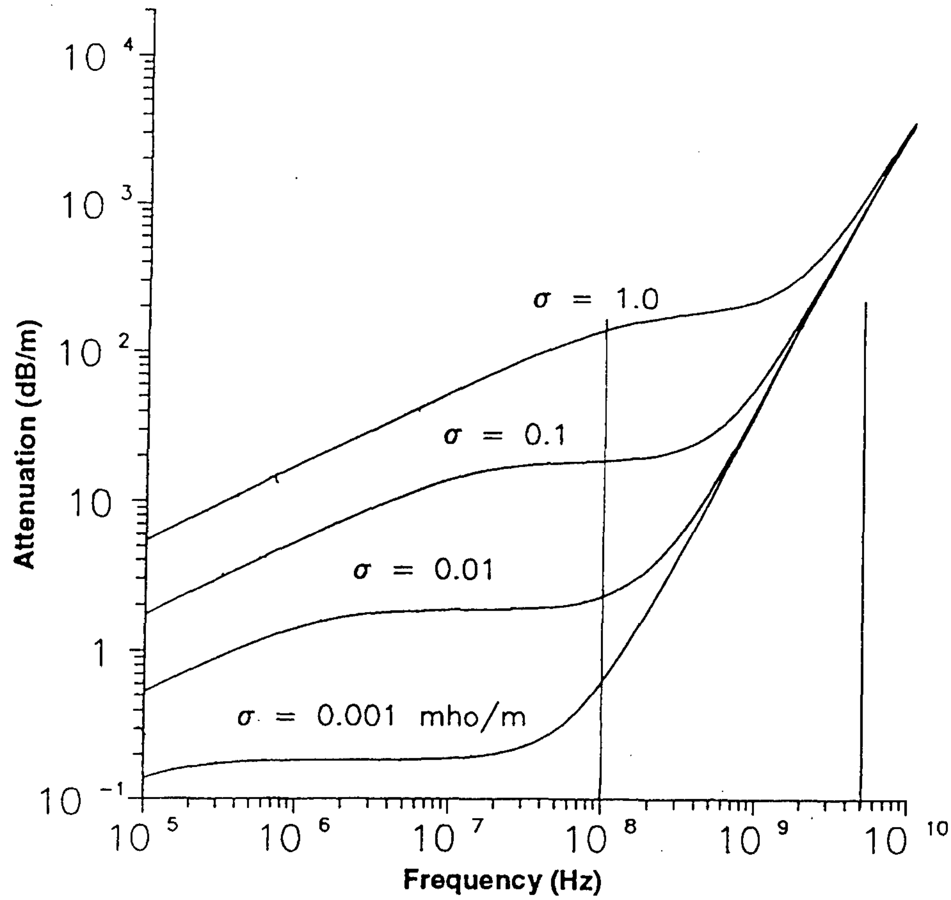

Figure 2. Attenuation of Radar Waves as a Function of Frequency in Wet Soils

in Wet Soils

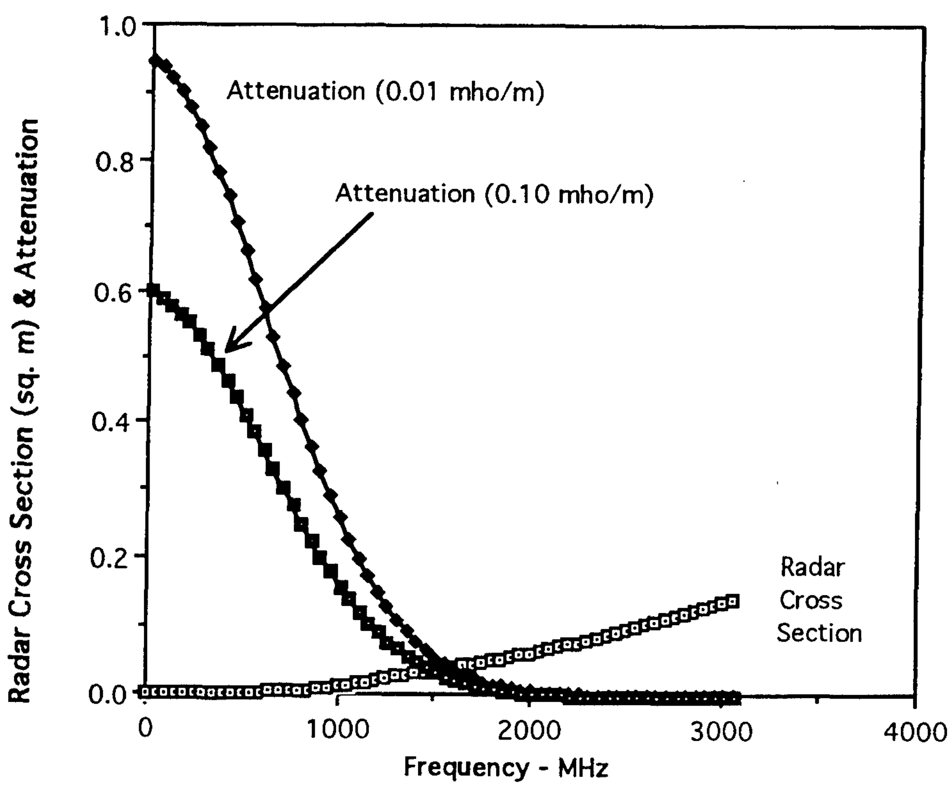

Figure 3. Effect of Attenuation Through 4.8 in. of Soil on Signal Transmitted and Radar Cross Section of 4.5-in. diameter Mines

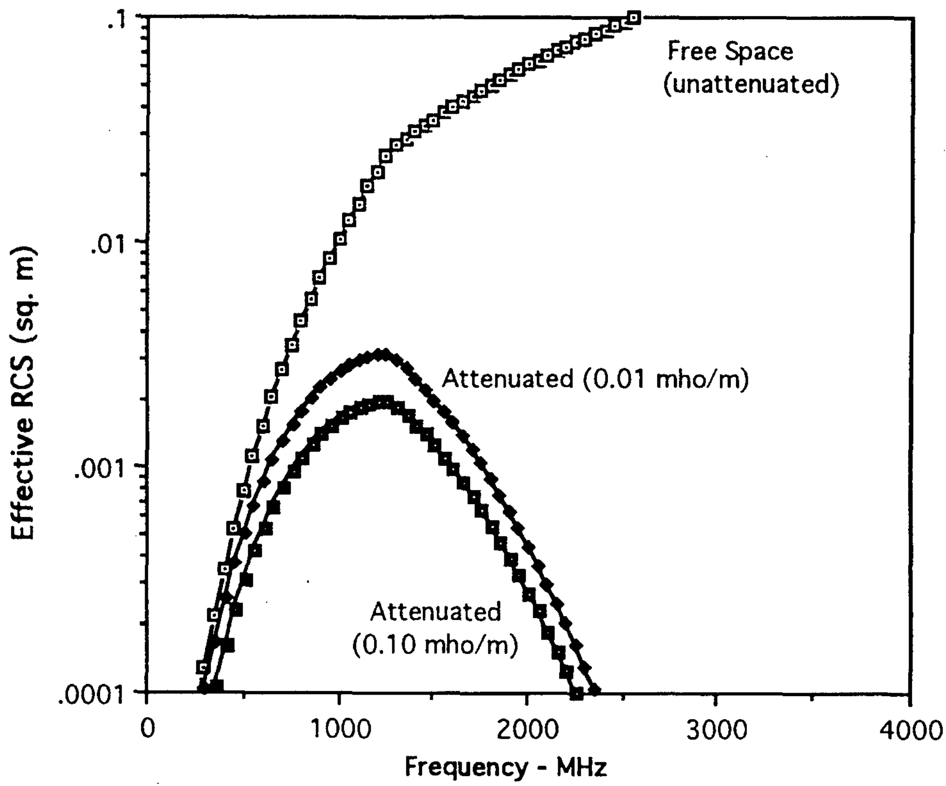

Figure 4. Effective RCS for 4.5-in. Mines

The effective cross sections, although small, are sufficient to significantly exceed system noise at the short ranges involved in a ground-based GPR application. The question is whether returns from mines can be distinguished from the competing signals from background clutter. The bar chart in Fig. 5 shows the integrated response, or effective cross section, for a high-frequency, wide-band radar with a uniform power density from 1 to 3 GHz. The response of a 4.5-in. mine buried at 4.8 in. is comparable to the response from a 3-in. stone at half that depth, a 2-in. stone just under the surface, and is much smaller than the response to a 3-in. stone near the surface, assuming the mines and stones have similar dielectric constants. A threshold setting that allowed detection of these mines would also report myriad small stones at shallower depths as targets.

Armed with foreknowledge of the size and depth of the mines, it is possible to optimize the radar waveform to discriminate against smaller stones. However, any stones of the same size as the mines but shallower will still give competitive signals. Furthermore, an optimization focused only on discrimination against small stones drives one into the Rayleigh region and significantly reduces the cross section for scattering from the mines. Finally, a technology that requires knowledge of both size and depth of target for reliable performance is unlikely to have much practical value.

The only prospect for high probability detection with low false alarms of 4.5-in. buried mines would be in a setting that contains very dry soil that is relatively homogeneous, except for the emplaced mines. This would include laboratory demonstrations and shallow mines emplaced in some roadbeds or on test ranges in desert regions.

DETECTABILITY OF PROJECTILES BY GPR

Projectiles, unlike mines, will tend to be located at significant depth. For very deep projectiles, the attenuation will eliminate any practical possibility of detection with GPR. For projectiles relatively near the surface, we must again consider the discrimination problem. Consider the response of a 155-mm artillery shell, oriented horizontally and buried at a depth of 0.5 m. This is a relatively shallow depth to find a 155-mm shell and is also a characteristic range resolution cell size. High P_d, low false alarm detection of 155-mm projectiles will depend on how their response compares to that of natural objects closer to the surface.

In Fig. 6 we present the attenuation for two values of the conductivity and the cross section, in arbitrary units, for a cylinder of length 620 mm and diameter 155 mm oriented perpendicular to the radar beam. Another way of viewing this is in Fig. 7, where the free space and attenuated responses are plotted as a function of frequency. From

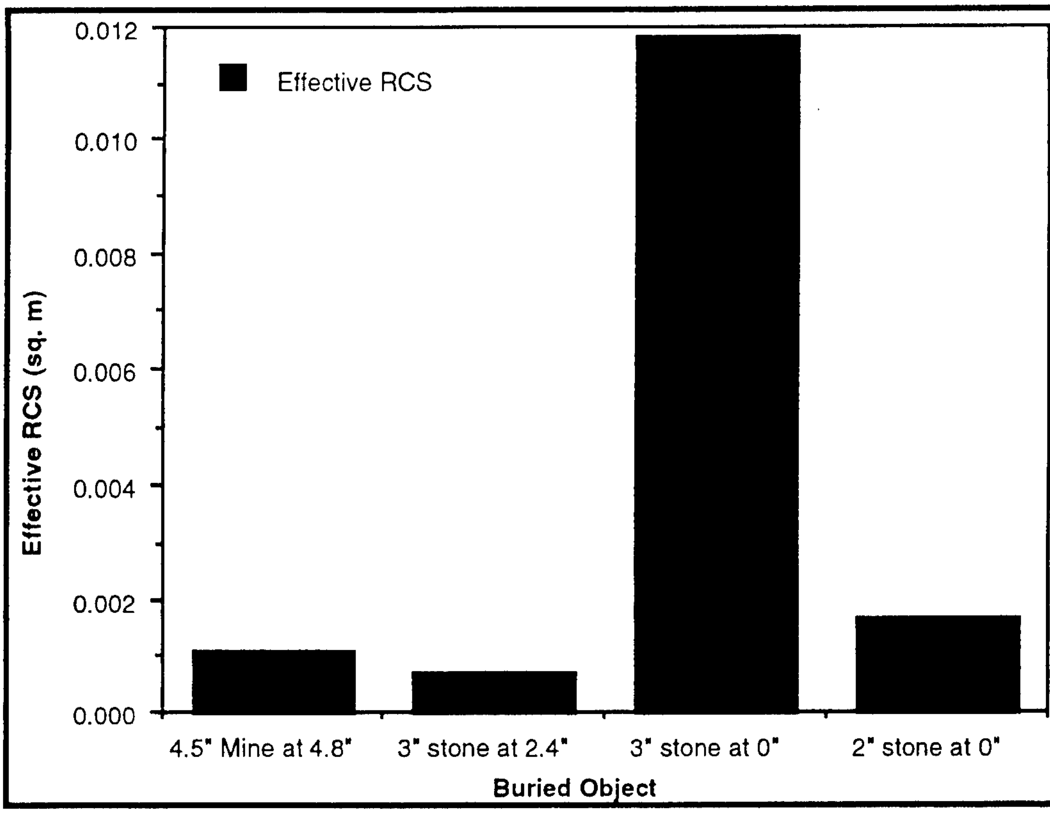

Figure 5. Effective Cross Sections for Various Objects

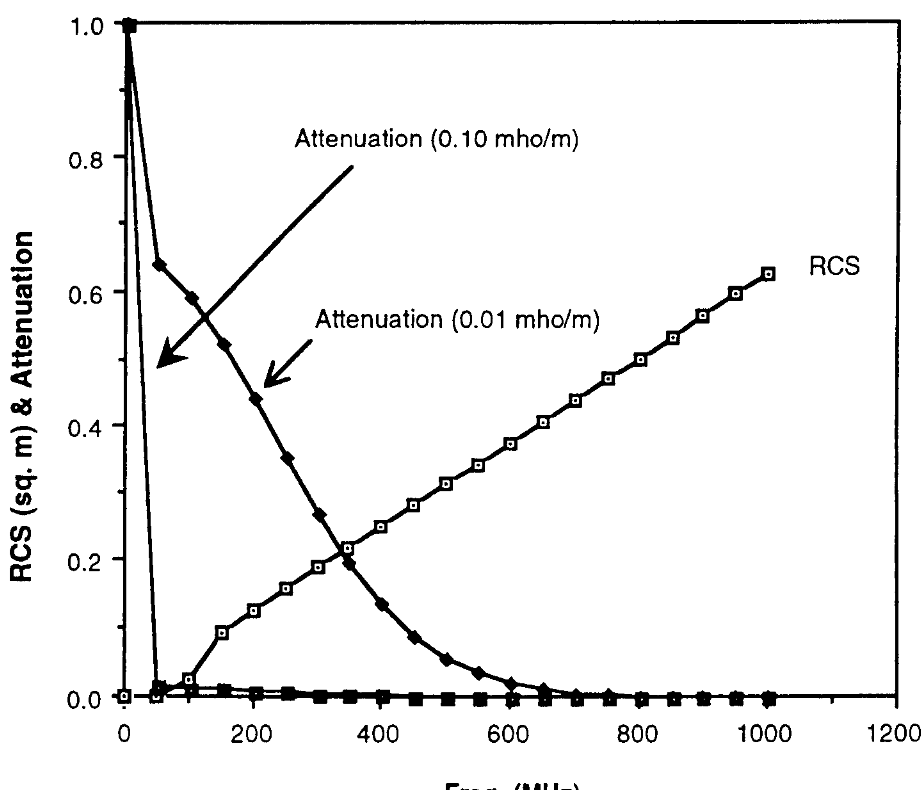

Figure 6. Effect of Attenuation Through 0.5 m of Soil on Signal Transmitted and RCS of 155-mm Projectile

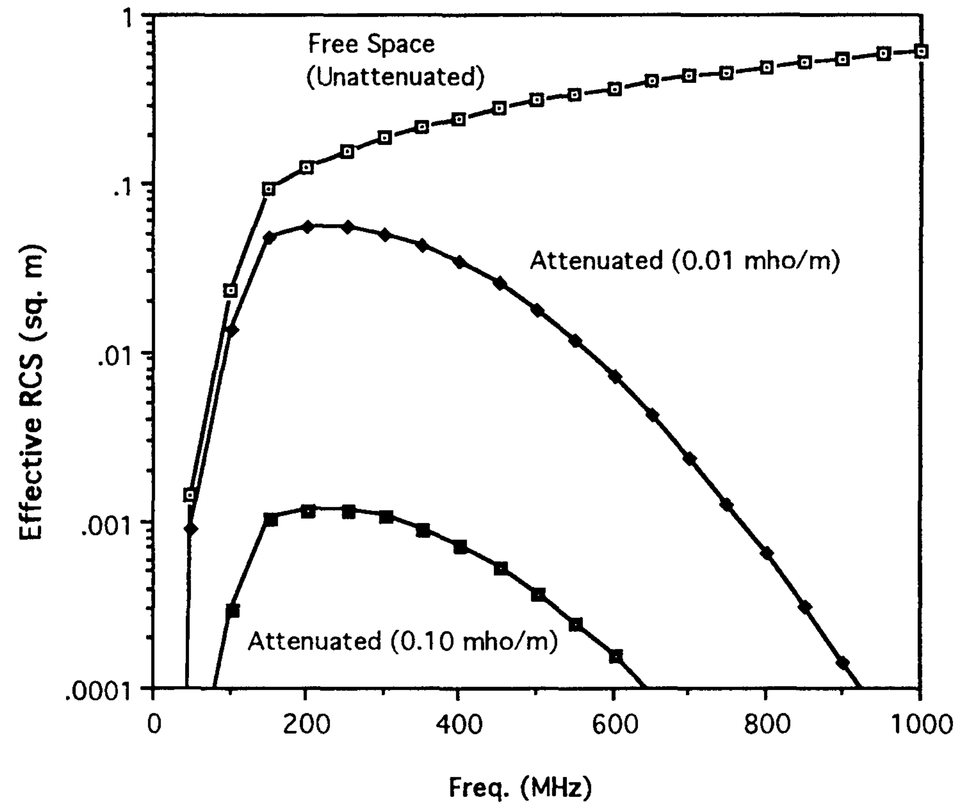

Figure 7. Effective RCS for 155-mm Cylinder

these figures we see that 0.01 mho/m conductivity would not have had significant impact upon the detectability of these shells, but 0.1 mho/m conductivity reduces the signal by two orders of magnitude. The responses to a 155-mm shell modeled this way are less than or equal to the response of a 20-cm flat rock near the surface. In most terrain, this is a common enough occurrence to cause significant background problems. However, as the figure indicates, for lower conductivities in the 0.01 mho/m range, radars operating below around 500 MHz show only modest reduction (less than an order of magnitude) of the full free space response to shells of this size. Hence, the false alarms will be driven by rocks the same size as the shells. Rocks this size are perhaps a rare occurrence, but probably one which is inescapable.

For mines, recall the long wavelength response is too small to be useful and the short wavelength response is attenuated by water in the soil. Artillery shells, on the other hand, are large enough to scatter longer wavelength radar waves. The attenuation of these waves is less than that of short waves and depends upon DC conductivity, rather than soil moisture. At sites where the conductivity is very high, deep shells will not be reliably detected and discriminated from background objects. At a site with lower conductivity, the same shells at the same depths might well be distinguishable from underground clutter by a radar with a well chosen band.

OBSERVED PERFORMANCE OF GROUND-PENETRATING RADARS

Two experiments provide the primary sources of information regarding GPR performance in near real world conditions, where detailed knowledge of the ground truth is not available: the JPG Advanced Technology Demonstration and the Yuma Proving Ground Radar experiments. In both tests, GPR detection capability was poor.

The high ground conductivity at JPG provides a partial explanation for the poor GPR performance (U.S. Army Environmental Center, 1995; Altshuler, et al., 1995), but similar difficulties were observed in the 1993 tests of airborne GPRs at Yuma Proving Ground.

The Yuma tests were technical rather than operational in emphasis, and allowed for detailed analyses of the losses. Studies by Lincoln Laboratories into the source of the difficulty in target detection have been published (Lee, 1994).

The results from the Yuma experiment are consistent with the JPG findings.

- Small targets near the surface cannot be distinguished from clutter objects because their cross sections are similar.

- Physically larger ordnance items, which tend to be buried deeper, have a large free space cross section, but the interface and propagation losses are so great that these objects also are largely undetectable.

DETECTION OF ORDNANCE BY INFRARED SYSTEMS

Infrared systems respond to the thermal radiation emitted or reflected from objects. All objects emit radiation, with both the total amount and spectral distribution depending upon their temperature and emissivity. For the application to ordnance detection, reflected radiation is unlikely to be significant. As a practical matter, only radiation in certain wavelength regions propagates through the atmosphere. Hence, development has focused on detectors that operate in the so-called "windows" in the 3–5 micron and 8–12 micron wavelength regions. Objects at temperatures of a few hundred degrees Celsius primarily radiate in the 3–5 micron region, whereas objects at room temperature primarily radiate in the 8–12 micron region. For the detection of ordnance items, unlikely to be more than a few degrees different in temperature from their surroundings, the 8–12 micron region is usually used.

Infrared systems can be used for detection in two regimes. For well resolved targets, images can be formed and examined, provided there is sufficient thermal contrast within the images. Typical modern systems readily form useful images if the contrasts are on the order of tenths of a degree C or larger. Alternatively, very hot objects can be detected by simple thresholding even when they are too small to form recognizable images. The most notable example of the latter is the use of infrared search and track systems to detect and track aircraft at long ranges in clear weather. The distant aircraft occupy a solid angle much smaller than a single element of the image (a picture element or "pixel"), yet the heat from aerodynamic friction and from the engines is sufficiently large that the aircraft are detectable. Often, aircraft can be detected with reasonable false alarm rates even against clouded (cluttered) backgrounds. As a practical matter, in a cluttered background the contrast must be so high that simple thresholding reduces the false alarm problem.

The IR signal from unexploded ordnance heated by the sun is unlikely to be sufficiently high or different from its surroundings to allow sub-pixel detection. Natural variations in temperature, emissivity, and heat capacity will overwhelm the thermal signatures of ordnance items with false alarms. However, detection of ordnance items with good false alarm rejection based on multiple pixel images is possible under certain conditions. The critical parameters controlling the performance of multiple pixel detection are discussed below.

CRITICAL FEATURES AFFECTING THE INFRARED DETECTION OF ORDNANCE

IR systems may, under optimal conditions, be useful for the detection of multiple-pixel-sized objects. In this case, the contrast requirements are much lower than for subpixel detection. Sufficient thermal contrast is required to exceed system noise and allow clear image formation. Unlike the case for subpixel detection, the contrast need not be great enough to eliminate false alarms by thresholding. Instead, false alarms are reduced or eliminated by recognizing or identifying the target object. There is considerable experience in recognition/identification of combat vehicles with forward looking infrared systems (FLIRs). In fact, recognition and identification have specific meanings, i.e., "recognition" means distinguishing a tank from a truck and "identification" means distinguishing one model tank or truck from another, e.g., an M-60 tank from a T-72 tank. Given that the contrast is sufficient so that system noise is not a problem, typically 50 percent probability of correct recognition and identification is achieved with 6 or 8 pixels, respectively, across the smaller presented dimension of the target.

We will use the criteria for recognition, 6 pixels across the small dimension, as a surrogate for detection of ordnance with a reasonable prospect of discriminating against clutter. (For objects with a very high aspect ratio, 6–8 pixels along the large dimension will often suffice.) This surrogate will apply if thermal contrast is adequate. As a practical matter, this requires, among other things, good solar loading and no precipitation. The models in use were developed to compare the performance of different systems averaged over a collection of targets, not to predict the performance of a specific system. This imposes limitations on the use of these models. However, it clearly identifies the approximate number of pixels on target needed for reasonable detection and discrimination performance.

For a buried object, the temperature differences between the object and its surroundings depend upon the relative heat capacities and conductivities of the object and the soil. In general, as the ground warms and cools during the diurnal cycle there will be a lead or a lag in the temperature of the buried object. This underground temperature difference is represented on the surface by a blurred image with a smaller temperature difference. Furthermore, the original temperature difference between the ordnance and the earth is likely to be smaller if the ordnance item is buried, since the item is heated via conduction through the soil, rather than directly via sunlight. All of these effects make the infrared detection of buried objects significantly more difficult than detection of exposed objects.

In Table 3 we present the approximate narrow dimension of an ordnance item (in mm) with a reasonable probability of being both detected and correctly discriminated from background clutter (i.e., 6 pixels across the narrow dimension) for several FLIR systems at several altitudes, including those demonstrated at JPG. The calculations labeled RAH-66 use a 70 μradian detector resolution, based on specifications for the target acquisition FLIR for the RAH-66 Comanche. The corresponding resolutions for the other columns are 160, 940, and 350 μradians, respectively. The Safire and FLIR 2000 F are commercially available from FLIR Systems, Inc. To give a specific example, the RAH-66 FLIR would enable recognition of 105-mm shells at 750 ft and 155-mm shells at a range of 1,000 ft. In contrast, the Safire and the FLIR 2000 F would be unable to recognize a 155-mm shell above 500 ft even in the narrow field of view setting.

Table 3. Minimum Dimensions[a] in mm for Detection by Various FLIRs

Slant Range (ft)	*RAH-66*	*Safire NFOV* [b]	*Safire WFOV* [c]	*FLIR 2000 F NFOV*
resolution (μr)	70	160	940	350
250	32	73	429	160
500	64	146	859	320
750	96	219	1288	480
1,000	128	293	1717	640

[a] The minimum dimension is taken to be 6 multiplied by the single pixel resolution size on the ground.

[b] Narrow field of view.

[c] Wide field of view.

This situation can be further exacerbated by vegetation and terrain. Both can obscure the view and interfere with the thermal heating and cooling of the ordnance items.

CONCLUSIONS

Each of the detection technologies investigated suffers from problems that limit its usefulness in detecting UXO. Because magnetometers rely on the magnetic signature of ordnance, which can be different based on history, orientation, and so on, detection can be difficult even for large magnetic objects. Background magnetic conditions can obscure magnetic signature. This problem would be amplified if the site requiring remediation is located in a region with a high density of magnetic minerals or man-made ferrous litter.

Detection by induction coils suffers from a $1/r^6$ fall-off in signal. A high density of conducting objects will obscure any UXO. GPR performance against mines will suffer from problems of discriminating between objects of interest and background clutter. Detection of larger objects may be possible in regions with low soil conductivity. Infrared detection of buried objects is challenging under all but the most favorable conditions. For heavily vegetated terrain it may be impossible.

One striking feature of the current approach to unexploded ordnance detection is that it focuses almost entirely on the detection of metal, usually magnetic, structural casing materials, rather than the detection of energetic compounds. Because of the preponderance of metallic debris on impact areas, systems that can detect high concentrations of explosives may provide opportunities for significantly reducing false alarms, so that limited recovery resources can be applied to activities that will reduce hazards. Of course, a technology that exploits other physical properties will be subject to other types of false alarms as yet uncharacterized. No techniques for directly detecting explosives are currently available for rapid field surveys.

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ARMY EXPLOSIVES SAFETY SUBMISSIONS FOR CLEANUP AND RELEASE OF REAL PROPERTY WHICH CONTAINS ORDNANCE AND EXPLOSIVES

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ABSTRACT

The Army is disposing of real property due to BRAC and normal property excessing. The Army manufactured, stored, fired, and disposed of ammunition on some of this property. In many cases, OE remains as a result. Before it releases the property, the Army will address OE consistent with how the property will be reused. However, the Army cannot proceed until its safety experts and the Department of Defense Explosives Safety Board (DDESB) approve an explosives safety submission. This article tells when to prepare a submission and when it must be approved. It also explains who approves them and what they should contain. This article concludes by giving lessons learned from past submissions.

DEFINITIONS

Active installations: Active installations are defined as installations still under the custody and control of the Army. They include operating installations, installations in a standby or layaway status, and installations awaiting closure due to BRAC or any other reason. Examples include but are not limited to posts, camps (including National Guard camps), forts, depots, activities, ports, ammunition supply points, basic load ammunition storage areas and ammunition plants.

Anomaly review board: A technical group established to provide technical guidance and quality assurance oversight of the review and resolution of geophysical information related to unresolved anomalies at a site.

Chemical agent: A chemical substance that is intended for use in military operations to kill, seriously injure, or incapacitate a person through its physiological effects. Excluded from consideration are chemicals used by industry, riot control agents (such as tear gas), chemical herbicides, smoke (such as white phosphorous), and flame (such as napalm).

Chemical warfare material: Chemical agents; or military munitions containing chemical agents.

Ordnance and explosives (OE) - OE consists of either of the following:

First, OE includes live ammunition, live ammunition components, chemical warfare material, or explosives that have been lost, discarded, buried, fired, or expelled from demolition pits or burning pads. Such material is no longer under accountable record control of any DOD organization.

Second, OE includes soil mixed with a sufficient amount of an explosive such that the soil presents explosion hazards. The concentration of a particular explosive in soil necessary to present an explosion hazard depends on whether the particular explosive is classed as "primary" or "secondary".

Secondary explosives are bursting and boostering explosives; ie, they are used as the main bursting charge or as the booster which sets off the main bursting charge. Secondary explosives are much less sensitive than primary explosives; in other words, they are much less likely to react if struck. Primary explosives are those extremely sensitive explosives (or mixtures thereof) which are used in primers, detonators, and blasting caps. Guidance on whether a particular explosive is classified as primary or secondary is available from the author.

Soil containing 10 percent or more by weight of secondary explosives presents explosion hazards. Such soil is OE. For primary explosives, no level has been established. However, the Army Environmental Center is establishing a level. In the meantime, soils with primary explosives must be sampled and tested to determine if they present explosion hazards. Guidance on soil sampling and testing is available from the U.S. Army Environmental Center, Mr. Wayne

Sisk, (410) 612-6851.

Formerly used defense sites (FUDs): Formerly active DOD or War Department installations (or portions thereof) that have been released outside DOD custody and control.

On-site: The area containing OE and all areas in close proximity to the OE that are necessary to implement the OE removal.

Real property: Real property consists of land, buildings, and water bodies. Real property may contain OE as the result of manufacturing, weapons firing, training, demolition ground operations, disposal, loss, abandonment, or waste collection. Examples of such property include pads, pits, basins, ponds, streams, impact areas, maneuver areas, training areas, burial sites, and buildings used for ammunition or explosives operations.

Recovered chemical warfare material (RCWM). Chemical warfare material and/or associated equipment that was previously disposed of as waste, and surrounding contaminated media, that was discovered either by chance or during real estate recovery/restoration operations.

Response action. The process of reducing risk of public exposure resulting from military ordnance and explosives. Actions may include detecting OE and either eliminating its explosive properties on site or transporting it off site to a storage or demilitarization facility, isolation of the hazard, or other action necessary to protect the public.

Stakeholder: Federal, state, and local officials, community organizations, property owners and others having a personal or emotional interest, involvement or share or having a monetary or commercial involvement in the property to undergo an OE response action.

WHEN IS A SUBMISSION TO DDESB REQUIRED?

The Army provides DDESB a submission when there is a plan to release active installation property outside DOD, and the property contains OE which must be addressed consistent with the reuse of the property.

WHEN IS A SUBMISSION TO DDESB <u>NOT</u> REQUIRED?

There are four cases...

Not required for emergency responses by military explosives ordnance disposal (EOD) or Technical Escort Unit (TEU). EOD is the military's version of a "bomb squad". TEU is also a military "bomb squad", only TEU specializes in handling chemical warfare material.

Not required for emergency or time critical actions taken to abate an immediate, extremely high explosives hazard. Example: an area that contains hazardous munitions on the ground surface is discovered. The area is open to personnel. Immediate action must be taken to deny access and/or remove the munitions.

Not required for normal maintenance operations conducted on active ranges, such as sweeping a range for duds after a weapons firing exercise.

Not required for formerly used defense sites (FUDS). Please note that the previous three cases do not require a safety submission of any kind. However, a FUDS does require a submission. A FUDS submission contains has about the same information as submissions for property releases. However, FUDS submissions go to HQDA for approval, not DDESB. For more information on FUDS submissions, contact the author.

WHEN MUST THE SUBMISSION BE APPROVED?

DDESB must approve the submission before the OE removal starts. However, intrusive sampling is permitted prior to approval. Intrusive sampling consists of sweeping sample plots of land with metal detectors and digging up magnetic "hits" (called "anomalies") to determine if they are OE or just inert metal. Intrusive sampling helps estimate the types and amounts of OE expected at a site. This is useful information in a submission.

WHERE IS THE SUBMISSION ROUTED?

The installation prepares the submission and sends three copies to its higher headquarters (in Army parlance, to its "Major Command" [MACOM] safety office).

The MACOM safety office endorses the submission and sends two copies to the U.S. Army Technical Center for Explosives Safety (USATCES).

The USATCES Army-approves the submission and sends one copy to the Department of Defense Explosives Safety Board (DDESB).

The DDESB approves the submission.

The Corps of Engineers is also involved in the preparation and review of the submission. For more details, contact the author.

WHAT SHOULD A SUBMISSION CONTAIN?

Provide an explanation of why OE exists on the site. Describe what types of OE are known or suspected to exist on the site. For example, the site may have been an impact area for 105mm and 155mm high explosive artillery projectiles. In most cases, studies already exist which provide this information. There are many different kinds of studies. Some of their names are Inventory Project Reports, Preliminary Assessments (PAs), Historical Records Searches (HRSs), Archives Search Reports (ASRs), Safety Surveys, and Engineering Evaluations/Cost Analyses.

Include a map showing the things listed below.

The map must show the boundaries of the area(s) known or suspected to contain OE.

The map must show the boundaries of the parcels of land to be released. In a typical base closure, the Army releases different parcels to different parties. Federal, state, and local agencies may get their own parcels. Private parties may get their own. Explain who will get each parcel and what they plan to use it for. There are many possible uses. Try to fit the use into one of these categories: residential construction, commercial construction, recreational construction, surface recreation, agriculture, vehicle parking, surface supply storage, livestock grazing, wildlife preserve.

The map or accompanying text should show how the OE will be addressed in each parcel. In most cases, a removal is planned. The removal depth is related to the future use of the property. For example, it would not be safe to remove OE to a depth of only one foot on property to be released for construction of an amusement park. For more information on removal depths and land reuse, contact the author.

For areas containing explosives-contaminated soil, provide a separate map showing the location of sampling points. Identify the concentration of explosives for each sampling point. Describe the screening method used to determine explosive concentration.

In addition to maps, provide the rest of the information below. Tell when the OE removal will begin.

State the depth of the frost line for the area. Where OE is above the frost line yet located below the removal depth, describe what provisions will be made for continued surveillance of the area (frost heave will push OE upward).

Describe the techniques to be used to detect, recover, and destroy OE. These techniques can be (but don't have to be) described by using excerpts from the work plan for the OE removal. If the work plan has not yet been finalized, a draft is acceptable. Any changes subsequently made to the draft that change the information in the explosives safety submission will be submitted for approval through the same channels as the submission.

State whether an Anomaly Review Board will be established for the OE removal.

If the onsite method to destroy UXO is something other than detonation (examples: bioremediation, incineration, etc.), then provide a brief description of the method.

Describe methods to be used to deny unrelated personnel access to areas hazarded by OE recovery and destruction operations. This hazarded area is called the "exclusion area".

If recovered OE cannot be destroyed on site and must be transported off site, indicate the transportation, storage, and disposition plans.

Summarize explosives ordnance disposal (EOD) or contractor support. If available, furnish resumes of the contractor's key supervisory personnel (the Army hires a contractor to do the actual OE removal).

Summarize any land use restrictions to be placed on the property. Land use restrictions are needed when the removal depth is less than the OE depth.

For chemical warfare material removal projects, provide details of the selected chemical protective clothing and equipment, air monitoring plan, maximum credible event, downwind hazard modeling, medical support plans, Technical Escort Unit Operating plans, etc.

Provide details of the public planning document(s) that ensure involvement of public and local officials where there is a risk to the public as a result of the removal action.

LESSONS LEARNED ON SUBMISSIONS

Submissions are slow moving beasts, and take a lot of care and feeding. It typically takes 3 months to prepare a submission and another three to get it approved. There are ways to speed up the process...

Get the key players together early - the preparer, the installation BRAC and safety offices; the MACOM BRAC and safety offices; the U.S. Army Engineering and Support Center, Huntsville (USAESCH) and the USATCES.

All parties in the Army review chain should review drafts of the submission.

Send the official submission to the MACOM, the USAESCH, and the USATCES simultaneously. This is faster than a sequential review.

SUMMARY OF THE DEPARTMENT OF DEFENSE DRAFT RANGE RULE

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The Department of Defense is developing a Range Rule that identifies a process for initiating and conducting response actions on closed, transferred, and transferring military ranges. The regulation will address explosives safety, human health, and environmental concerns related to military munitions and other constituents on these ranges. The Department is promulgating these regulations pursuant to authorities set forth in the Defense Environmental Restoration Program (10 U.S.C. 2701-2707), Department of Defense Explosives Safety Board (10 U.S.C. 172), and the Comprehensive Environmental Response, Compensation, and Liability Act (42 U.S.C. 9601-9675).

This rulemaking is also based, in part, on the Environmental Protection Agency's (EPA) proposed Military Munitions Rule (60 Fed. Reg. 56468, Nov. 8, 1995). In EPA's on-going rulemaking, the Agency recognized the Department's legal authority to establish regulations for military ranges, as well as the Department's unique expertise in addressing the explosives safety risks inherent in military munitions. The Agency stated that the Department's rule would supersede those proposed by the Agency, if it fully protects human health and the environment. In addition, the Department's rule must provide for public and regulatory involvement throughout the process. The Department believes it has met this challenge in this draft Range Rule and looks forward o promulgation of a final Rule by October 1996.

The Department is promulgating these regulations in accordance with the Administrative Procedures Act. It has sought to facilitate discussions with the public, regulators, and other federal agencies by publication of this pre-proposal draft. In addition, the Department has discussed, and will continue to discuss, its proposal with stakeholders throughout the rulemaking process. The Department expects to publish the proposed rule in the Federal Register in April 1996, followed by a formal 60-day public comment period. The draft Range Rule sets forth a comprehensive process for identifying, evaluating, and addressing military munitions and constituents on closed, transferred, and transferring ranges. That process ensures not only public safety, but also the safety of response personnel, while addressing human health and environmental concerns. Important provisions of the proposal are summarized in the following pages.

DOD RANGE RULE OVERVIEW

The process for addressing closed, transferred, and transferring military ranges has five basic phases: (1) Range Identification, (2) Range Assessment/Presumptive Response (3) Range Evaluation/Site-Specific Response, (4) Recurring Review, and (5) Range Close-out.

RANGE IDENTIFICATION

Under the Range Rule, the Department of Defense would identify all land and water closed, transferred, and transferring ranges subject to the rule. As defined in the draft rule, a military range is any designated land, air or water area used for training with military munitions, or any area used for munitions research, development, testing, or evaluation. The draft Range Rule also defines the following categories of ranges:

Closed Range: A closed range is one that is taken out of service by the military and put to a new use that is not compatible with range activities. A range is considered closed, for example, when construction of buildings in that area have made it unsuitable for range use. Closed ranges are typically under the control of the military.

Transferred Range: A transferred range is one that has been released from military control. These areas are a subset of Formerly Used Defense Sites. Some of these ranges have been transferred to other federal agencies such as the Department of Interior or Department of Energy. Others have been transferred to state or local governments, or to private citizens.

Transferring Range: Portions of military ranges are being considered for transfer outside of military control. These include ranges under the Department of Defense Base Realignment and Closure program, as well as other property transfer agreements. Transferring ranges remain under military control until they have been officially transferred to another party.

The draft Range Rule does not address the management of military munitions or constituents on Active or Inactive Ranges. Active Ranges are those that are being used by the military for training, research, development, testing, and evaluation. An Inactive Range is one that is not currently being used, but is held in reserve by the Department of

Defense in the event the Department has a change in mission that requires its use. The management of active and inactive ranges comes under existing Defense Department and Service regulations. The proper safety-based management guidelines for unexploded ordnance at active and inactive ranges will be addressed in a forthcoming policy to be issued by the Department of Defense Explosives Safety Board.

During the Range Identification phase, detailed information about the ranges would be recorded in a centralized range tracking system. The Defense Department would use this range inventory to assist in prioritizing ranges for subsequent response. For example, Transferred Ranges (those already outside of Defense control and in non-Defense use) would be addressed before Transferring or Closed Ranges, which are still within the Department's control. The Department will seek to ensure that a notice of the land's prior use as a military range is contained in official land records.

The Range Identification phase would also include public and state involvement in identifying the location of closed, transferred, or transferring military ranges. After verifying the accuracy of information received, the Department would enter the information into its central range tracking system. The Defense Department also plans to provide information on the identified ranges to federal agencies that develop and distribute official maps and charts.

RANGE ASSESSMENT/PRESUMPTIVE RESPONSES

Range Assessment. Once a range has been identified, the Department would assess the explosives safety, human health, or environmental risks the range might pose. This assessment would include collection of existing information on such factors as soils and geology, terrain, vegetation, climate, current and predicted land use, and other data useful in assessing risk. The Range Assessment would allow response personnel to distinguish between ranges where risks can be readily managed and those that warrant more detailed study and analysis. The Range Assessment may require a visual inspection of the range or some sampling of environmental media.

Presumptive Response. A Presumptive Response is any readily available, proven method of addressing the immediate risks, particularly explosive risks, posed by military munitions or other constituents on military ranges. When range conditions warrant a response, the Defense Department would implement a readily available, proven method of addressing the immediate risk.

Some examples of Presumptive Responses include:

1. Posting signs warning of danger associated with a range.
2. Erecting fences or taking other measures to control access.
3. Starting community education and awareness programs.
4. Installing monitoring wells to determine if substances are in the groundwater.
5. Conducting surface sweeps for unexploded rounds.

This is by no means a complete listing of the types of responses available to address the risks posed by ranges.

The Department would use information collected during the Range Assessment phase to determine which Presumptive Response measures are warranted. Additionally, information about the types of munitions used, reported incidents involving munitions, and information about the environmental setting of the range will also be helpful in assessing the risks and selecting an appropriate Presumptive Response. The primary difference between this type of response and a more complex, site-specific response is the scope of this evaluation. Consultation with federal and state agencies and the public, and public access to information, as well as a formal comment period, would play an important part in selecting a Presumptive Response or determining that a more in-depth Range Evaluation must occur.

RANGE EVALUATION/SITE-SPECIFIC RESPONSE

Range Evaluation. Range Evaluations are detailed investigations into the types of munitions used on the range, materials associated with these munitions, and the environmental setting. Information collected during this phase would be far more detailed than that collected during the range assessment. The primary purpose of the Range Evaluation phase is to assess the level of risk posed by the site and make an informed risk management decision. The Range Evaluation would be used to determine whether a Site-Specific Response is required and to provide an estimate of the overall risk posed by the range conditions.

Site-Specific Response. The Site-Specific Response evaluation examines various alternatives that address risks that have not been reduced or eliminated by responses taken earlier in this process. Each alternative would be examined in light of explosives safety requirements and nine criteria established by the National Contingency Plan. These criteria are as follows:

1. Overall protection of human health and the environment.
2. Compliance with applicable requirements of federal and state law.
3. Long-term effectiveness and permanence.
4. Reduction in explosives safety hazards, toxicity, mobility, quantity, or volume.
5. Short-term effectiveness.
6. Implementability (i.e., how feasible is it to implement the option?).
7. Cost.
8. Acceptability to appropriate federal and state officials.
9. Community acceptance.

It is important to note that safety is the overriding concern. Before taking any action on a range, a Site Safety Plan must be submitted to the Department of Defense Explosives Safety Board for approval. Consultation with state agencies and public access to information, as well as a formal comment period, would play an important part in decision-making. Restoration Advisory Boards or similar forums would be involved in the process leading to specific range response actions Because this phase would involve a complex study, it would generally be a long-term action.

RECURRING REVIEWS

The purpose of Recurring Reviews is to ensure that range response actions continue to ensure explosives safety and protection of human health and the environment. The Review would also determine if additional evaluation is required. The focus of the Review would depend upon the original purpose and nature of the response. The Defense Department proposes that the initial Recurring Review of closed, transferred, and transferring ranges be conducted three years after a Presumptive Response or Site-Specific Response is taken, or as necessary to ensure that the response action is still effective. Subsequent Recurring Reviews would be conducted at years 7, 12, 18, 25 years, etc. after the response action. There would be an immediate review if an emergency situation is identified. Likewise, regulatory agencies and the public may request further consideration of the effectiveness of the response action outside the Recurring Review schedule. Consultation with federal and state agencies and the public, and public access to information, as well as a formal comment period, would play an important part in drafting the final report and decision document within this phase.

CLOSE-OUT

Following review to ensure that the range is unlikely to pose further risk, or that the response objectives were achieved, the Defense Department would end the response action. If at some future date a problem is discovered, however, the Department would address the problem as appropriate. Consultation with federal and state agencies and the public, and public access to information, as well as a formal comment period, would play an important part in this phase.

1 # The Military Range Rule

Karen Heckelman

UXO Forum

March 26, 1996

2

Purpose & Objective: Establish procedures for evaluating and responding to explosive safety, human health, and the environment on Closed, Transferring, and Transferred Ranges.

Scope & Applicability:

Who:	"DoD Components" (Military Services and NGB)
What:	Closed, Transferred, Transferring Ranges
	Owned, leased, otherwise possessed by DoD
Where:	U.S., Puerto Rico, Guam, Virgin Islands
Note:	DoD Instruction for Active and Inactive ranges
	Military Ranges with prior agreements
	DoD emergence response will continue for Historic Battlefields

3 **RESPONSE IS FULLY PROTECTIVE OF HUMAN HEALTH/ENVIRONMENT**

4

5

6 **PROMULGATE UNDER EXISTING DoD AUTHORITIES**

- 10 U.S.C. 2701 - DEFENSE ENVIRONMENTAL RESTORATION PROGRAM (DERP)
- 10 U.S.C. 172 ("DDESB")
- 42 U.S.C. 9601 CERCLA/E.O. 12580/NCP

7 **RULEMAKING TO FULLY INVOLVE PUBLIC AND STATES**

- PRE-RULE WRITING INITIATIVES
- RANGE RULE AVAILABLE ON WORLD WIDE WEB
  - http://www.acq.osd.mil/ens/
- DEVELOPMENT OF PUBLIC INVOLVEMENT PLAN
- REGIONAL ENVIRONMENTAL COORDINATORS OUTREACH TO STATES
- INFORMATION CENTER OPERATIONAL
  - 1-800-870-6542
  - E-MAIL - FBARRULE@B-R.COM

8 **DOD RULE WILL INVOLVE STATES**

- PROCESS SIMILAR TO CERCLA
- ARARs
- COORDINATION OF DOCUMENTS
- RAB/EXTENDED PROJECT TEAMS
- NOTIFICATION TO STATES
- ACCESS TO INFO
- NATIVE AMERICANS

9 **RULE HAS PUBLIC INVOLVEMENT AND SIGNIFICANT ROLE IN RESPONSE**

- RESTORATION ADVISORY BOARDS
- EXTENDED PROJECT TEAMS
- ACCESS TO INFORMATION
- NOTICES

- PUBLIC AVAILABILITY SESSIONS/MEETINGS
- PUBLIC COMMENT PERIOD

10 CRITICAL PATH MILESTONES

- ***ESTABLISH WRITING TEAM*** ***15 DEC***
- ***START PRE-RULE MEETINGS*** ***1 FEB***
- ***DRAFT RULE (EPA/OMB/OTHER FEDS)*** ***23 FEB***
- ***PREAMBLE ON WWW*** ***1 MAR***
- RULE TO OMB 18 MAR
- PUBLISH PROPOSED RULE IN FR 24 APR
- DoD FINAL RULE (EPA/OTHER FEDS) 6 AUG
- PUBLISH FINAL RULE IN FR 1 OCT
- EFFECTIVE DATE FOR RULE 31 OCT

Explosive Ordnance Disposal Technology Coordination

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ABSTRACT:

The Department of Defense Explosive Ordnance Disposal (DODEOD) Program is chartered to provide technology and training for military EOD forces. All of the technologies developed under this program are related to the detection, access to, identification, render safe and disposal of Unexploded Explosive Ordnance (UXO). Coordination of these technologies is accomplished through a yearly planning cycle that culminates with the adoption of a cohesive EOD technology plan by the DODEOD Program Board. This paper will address the factors behind the establishment of the needs for this plan and the technical programs planned to fulfill these needs.

INTRODUCTION:

A technology assessment was performed in 1992 to determine the military EOD needs for technology for missions related to UXO. After review of this assessment a plan was established to address five major need areas: Clearance of Improved Conventional Munitions (ICM), Improvement of General Tools, Response to Improvised Explosive Device/Special Improvised Explosive Device Incidents, Standoff Detection of Ordnance and Neutralization of Underwater Ordnance. These areas provide the framework for coordinating EOD UXO work funded under 6.1, 6.2, 6.3, MFP-11, 6.4 and congressionally mandated funding.

ICMs are the family of explosive ordnance that are deployed in air dropped, tube launched or hand emplaced canisters and dispensed over a wide area. This family includes mines, anti-vehicle (armor and soft skinned), anti-material and anti-personnel submunitions. Hundreds of these submunitions are contained in a single bomb, artillery round or rocket. The EOD Technician now must deal with all of the small UXO items in each round rather than the single round. Many of these ICMs contain Electronically Safed and Armed Fuzes (ESAFs) which contain advanced sensors. The major needs in this area are to develop robotic and standoff techniques for determining the status of the fuzes and removing the ICM from battlefields, ranges and formerly used defense sites.

Detection of deeply buried (>10 ft) ferrous ordnance and shallow buried (>4 in) non-ferrous and plastic UXO is a problem for EOD Technicians for area clearance, runway repair and active range clearance. The proliferation of ICM provides a surface contamination threat that is difficult to detect with the naked eye in even light foliage conditions. A wide range of Commercial off-the-shelf (COTS) sensors and signal processing algorithms are currently being demonstrated by the Naval EOD Technology Division (NAVEODTECHDIV) for the Army Environmental Center (AEC). This area extends the capabilities of the most promising of these technologies for use by individual EOD Technicians.

The Navy EOD Diver is called upon to perform render safe operations against all types of threats located in shallow to very shallow water. This area focuses on providing the EOD Diver with technologies that will increase their ability to find and examine underwater threats prior to performing the render safe operation.

EOD technicians historically have used explosively driven tools and remotely operated vehicles to perform render safe procedures. Needs also exist to improve remote vehicles, reduce the signature of EOD Technicians/Tools and to provide low influence communication equipment. This area focuses on providing near term solutions to these issues.

The EOD Technician is also called upon to search for, access, diagnose and disable devices that contain conventional and unconventional explosives that have been placed by terrorists or disgruntled persons. Increasing the capability to search for the device and any booby traps, avoid/eliminate booby traps, and examine and disable the device from a standoff distance will allow the EOD Technician to counter constantly increasing anti-intrusion sensor threats that are available from local hardware stores and electronic shops. This area will not be addressed in the body of the paper.

The development efforts in each of these mission areas are combined on EOD Technology Coordination Roadmaps. The roadmaps allow policy makers, resource sponsors, program managers and technologists to quickly review the EOD Technology program to determine the following:

(a) Major EOD missions are addressed and active programs are underway to support these missions.

(b) Funding for individual efforts is programmed and transition points are defined for moving efforts from one program element to another.

(c) Transition documentation is prepared and milestone decisions are scheduled to reduce overall development time for a single tool.

(d) Technology efforts outside of the current EOD efforts are leveraged to reduce cost and time to fielding.

The individual tasks in each mission area are established by two methods. The first method is the use of a Joint Service EOD (JSEOD) Notional Concept Paper (NCP). The NCP is a document prepared in accordance with a JSEOD Policy Agreement that allows the EOD Technician in the field to provide input to the requirements cycle. The NCP is forwarded from the field to the JSEOD Notional Concept Working Group. This group is made up of military members from each of the four services along with technical consultants from the NAVEODTECHDIV. If the NCP is supported by two or more of the military services, it becomes a JSEOD need. If the need is determined to require exploratory development or advanced technology demonstration work prior to becoming an acquisition effort, it is forwarded to the Office of Naval Research or the Office of Special Technology for their review and possible funding. If the need is determined to be ready for an acquisition program, it is forwarded to the JSEOD Program Manager in PMS-EOD which is responsible for joint service efforts.

Technology efforts can also be started by being identified as a high priority need in the EOD Technology Assessment. The NAVEODTECHDIV works with the Military Technical Acceptance Board to determine emerging needs of the EOD community and identify which of these needs require a long term exploratory development solution. This assessment is currently being updated.

After a decision is made to begin an effort in support of an NCP or high priority technology, three major funding sources are used. The Office of Naval Research funds the basic research and exploratory development work. The Office of Special Technologies, EOD/LIC Program funds rapid prototyping/advanced development efforts. PMS-EOD funds the advanced development efforts. Additional funds are also provided by the Office of the Secretary of Defense-Joint Robotics Program and the AEC.

AREA: CLEARANCE OF IMPROVED CONVENTIONAL MUNITIONS

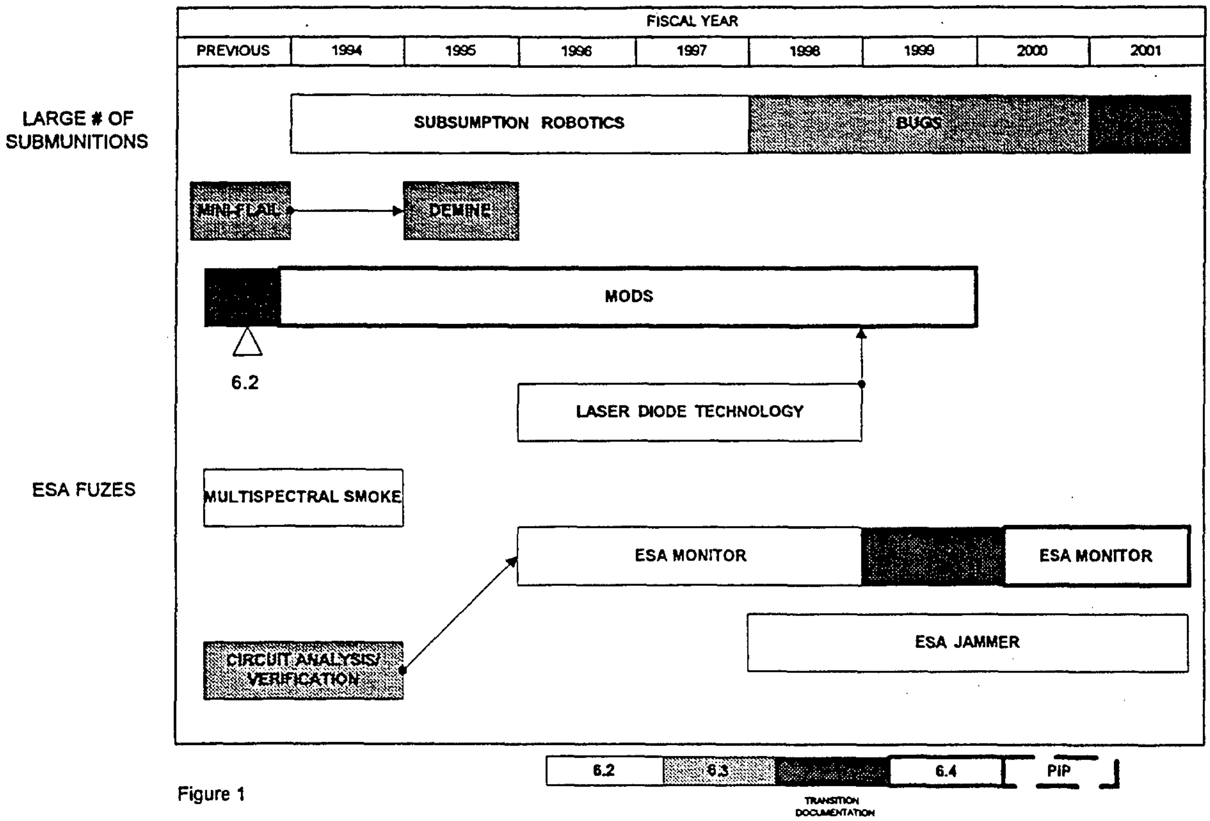

Figure 1

AREA: STAND OFF DETECTION OF ORDNANCE

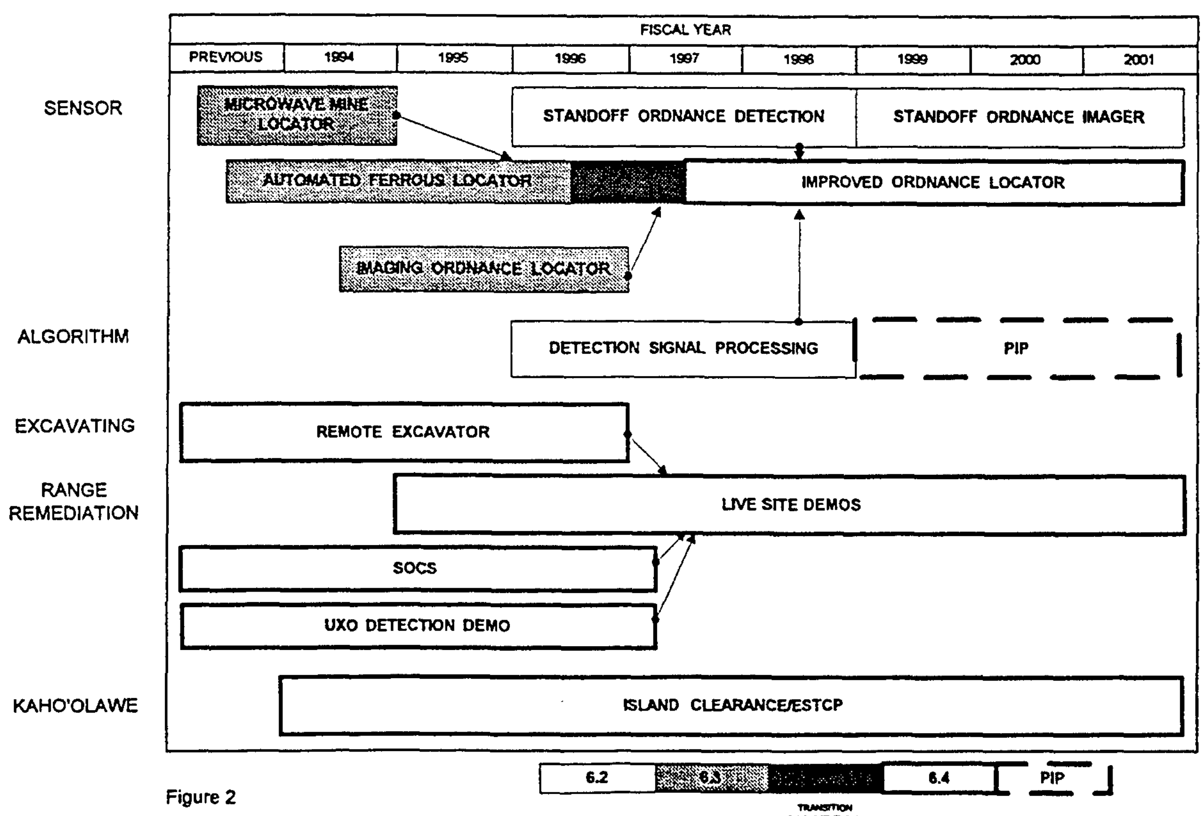

Figure 2

Clearance of ICM:

The EOD Technician traditionally clears ICM by one of three methods. The first is Pick Up and Carry Away (PUCA). This is a simple but risky operation of walking up to a UXO item, determining the state of the fuzing and if safe, picking up the UXO item. This technique is most frequently used in time of conflict when time is critical. The second method is Blow in Place (BIP). In the BIP operation each UXO item is countercharged with a block of explosive and blown up. This method is time consuming and may have a negative environmental or collateral damage impact. The last technique is Small Arms Munition Disruption (SMUD). A rifle, .50 caliber, 7.62 mm or 5.56 mm, is used to shoot a round at the UXO and cause a mechanical disruption of the fuzing or a reaction in the main explosive charge. SMUD is a rapid, standoff technique but the skill of the operator deteriorates with time. If the UXO is not hit in the proper spot, the item becomes an unknown hazard and must be dealt with on a one-by-one basis.

The introduction ESAFs into ICMs has greatly complicated all of these procedures. In order to get close to an ICM to perform PUCA or BIP operations, any anti-tampering devices must be dealt with. The use of electronic intrusion alarm devices rather than trip wires or pressure triggers greatly complicates the inspection process. ESAFs may also be incorporated inside the main explosive charge and be inductively armed. The inability to accurately determine the status of the ICM fuze before and after SMUD operations reduces the utility of this technique also.

Two major areas are under investigation in the Clearance of ICM area to address these concerns. Figure (1) shows the road map for this area. The first is the clearance of large numbers of ICM. Two efforts are underway to improve the safety and performance of the SMUD and PUCA/BIP missions. The Mobile Ordnance Disruption Systems (MODS) has been developed by the Air Force, Air Base Operability Office and JSEOD. This system uses a two kilowatt laser to disrupt UXO from a standoff distance. The laser removes the inaccuracies of rifle fire by providing the operator with a visible spot on the UXO prior to turning on the main laser. The laser causes the explosive in the UXO to burn or causes a small detonation that breaks the UXO up. Current efforts center around reducing the size, power requirement and cooling requirement for the laser to allow the system to be deployed on a HUMMV.

The second effort is the Basic UXO Gathering System (BUGS). The BUGS concept is to replace the human in the PUCA/BIP operation. A high cost sensor platform will survey the area containing UXO. A map of target locations will be made and passed to small, inexpensive Basic UXO Gatherers (BUGs). The BUGs use commercial parts and low level behavioral control to reacquire the UXO and perform the PUCA or BIP mission.

Currently a technology study is underway to identify techniques for determining the status of ESAFs from a standoff distance. The study is addressing the following concerns:

(a) Determine if power supply has a charge
(b) Determine if the item is functioning
(c) Determine if the item is fuzed
(d) Determine the status of the fuzing

An outyear effort will address turning off the ESAF from a standoff distance.

Standoff Detection of Ordnance:

Currently EOD Technicians use hand held magnetometers and active electro-magnetic sensors to detect and localize buried UXO. All of the detectors are militarized versions of commercial equipment. The EOD community sees a need in the near future to replace these

detectors with a single detector that will provide a capability to detect and discriminate ordnance that is buried deeper, has lower metallic content and is in cluttered environments. Figure (2) shows the roadmap for this area.

Work in this area is guided by the results of testing being performed in the Jefferson Proving Ground (JPG) demonstrations. The highest scoring demonstrations have been those using magnetometers and active electro-magnetic devices. Two exploratory development efforts are currently underway to improve the performance of these sensor types. The first effort is examining the use of high temperature as a superconducting quantum interference device (SQUID) to improve the sensitivity of a hand held magnetometer. The second effort is based on a time domain active electro-magnetic approach. The work at JPG has also shown the strengths and weaknesses of using signal processing to enhance operator performance. An exploratory development effort is planned to use a model based neural network to enhance the discrimination capabilities of the operator.

The remainder of the work in this area support the AEC and the Naval Facilities Pacific Command. A majority of this work supports congressional mandated demonstrations of UXO clearance technology and the clean up of Kaho'olawe Island. The information gained from these efforts supports the EOD need for improved standoff detection of ordnance.

Improvement of General Tools:

The EOD Technician relies on a number of different tools and techniques to perform any mission. Remotely operated vehicles, explosive tools, low signature materials and communications are used for many different types of UXO. Significant efforts are underway or planned in each of these areas. Figure (3) shows the roadmap for this area.

The JSEOD community has been a leader in the fielding of remote systems and currently has over 250 systems in the field. Two efforts are underway to increase the capability to perform reconnaissance missions and perform EOD procedures on a wider variety of UXO. The first effort, the Remote Controlled Reconnaissance Monitor (RECORM), provides a capability to inspect UXO from a 650 meter standoff on either radio frequency or fiber optic control. The system is two man portable and is currently completing operational testing. The second effort is the Remote Ordnance Neutralization System (RONS). RONS will allow the EOD Technician to perform procedures on ordnance that is encountered in a field environment.

EOD Technicians currently use a large number of different explosively actuated tools to disrupt the fuzing in UXO. Two efforts are underway to add to this capability. The first is the Lightweight Disposable Disrupter (LIDD). LIDD is being designed to have the same performance as the current heavy barreled, slug throwing traditional EOD tools, but in a much smaller and less expensive package. The second explosive tool is the Main Charge Disrupter (MCD). MCD is needed to cause reliable low order detonations of large bombs and artillery rounds.

Neutralization of Underwater Ordnance:

Navy EOD divers have a unique responsibility to respond to underwater UXO incidents. These incidents range from very shallow water mine countermeasure missions to safing explosive items on downed aircraft. These requirements, along with land based EOD missions, put many demands on the Navy EOD community. Efforts are underway in the life support, equipment, point search and area search areas to increase the productivity of the Navy EOD diver. Figure (4) shows the roadmap for this area.

AREA: IMPROVEMENT OF GENERAL TOOLS

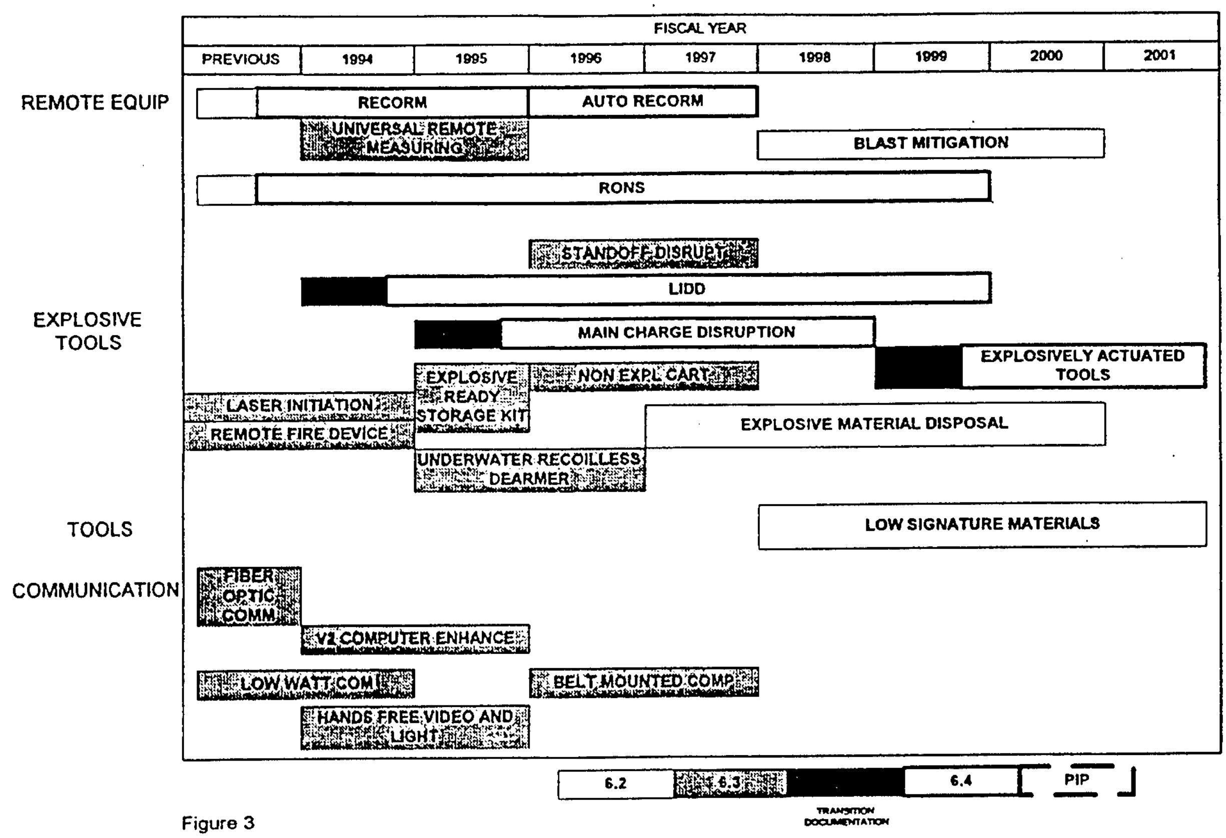

Figure 3

AREA: NEUTRALIZATION OF UNDERWATER ORDNANCE

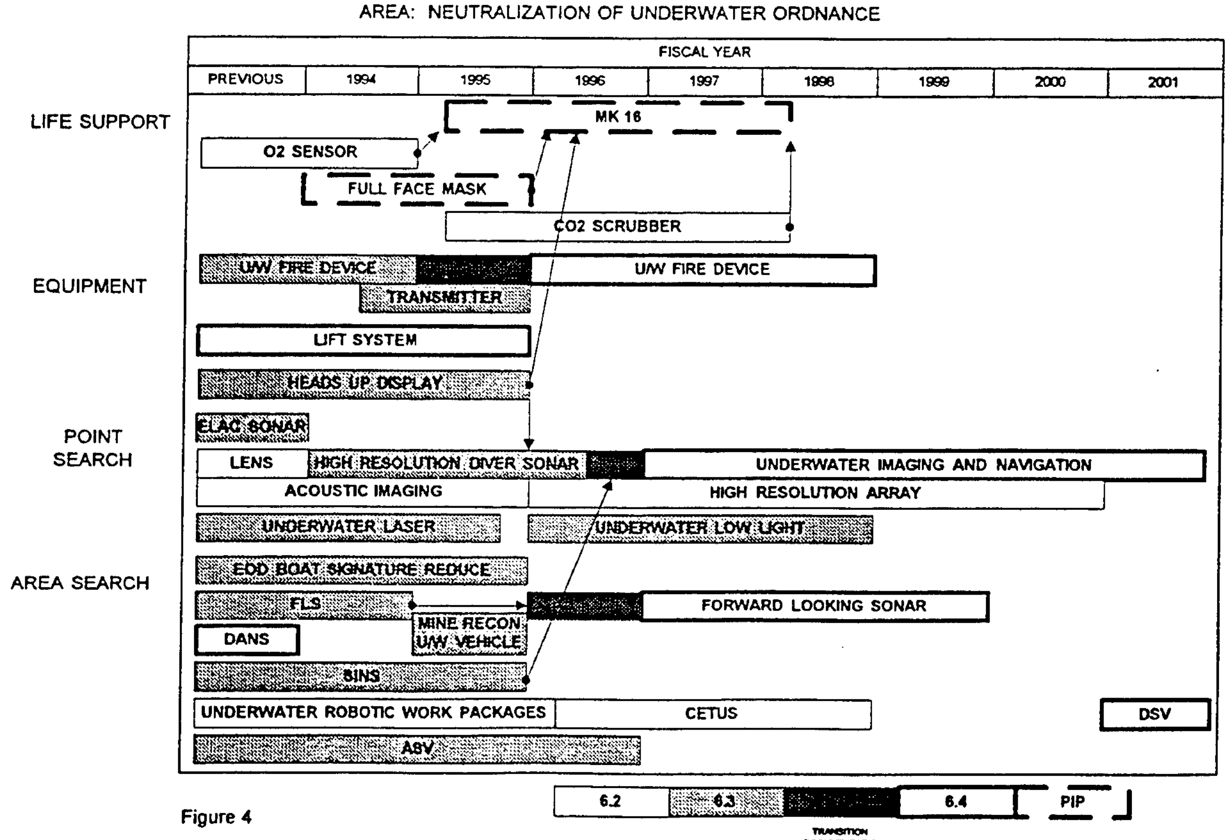

Figure 4

Life support and equipment efforts center on improving the performance of underwater breathing apparatus and other hand carried equipment. Point Search focuses on increasing the divers capability to search a small area to reacquire and identify underwater UXO. Major efforts in high frequency diver hand held sonars and electro-optic systems are underway. Electro-optic systems offer a telescope-like capability to inspect potential targets from a standoff distance. These systems work very well in clear water but their performance degrades in cloudy water due to scattering of the laser beam used to illuminate the target. Sonars do not provide a picture of the target but build three dimensional images based on the return of a sound pulse. The images are comparable to medical ultrasound pictures. The sonar is not affected by the clarity of the water but the image resolution and standoff is limited by the frequency selected for the sonar.

The last area addresses the search of a large area using small boats, small surface craft and small underwater vehicles. Navy EOD operates with whatever equipment they can carry on a C-130 cargo plane. Large boats and large remote vehicles are not practical for their use. This leads to technologies that are small and relatively inexpensive. Area search detachments currently use side scan sonar to hunt for targets in a lawn mower pattern. The search is slowed because a gap exists in the middle of the side scan sonar returns. The forward looking sonar effort is addressing this problem by providing a sonar that will search in front of a small boat and fill the gap in the side scan search. The search for UXO can also be accomplished by using remote surface or underwater vehicles. The Area Search Vehicle is based on a personal water craft and can tow a small side scan sonar to map an area. The Composite Exoskeleton Testbed UUV System is an underwater vehicle that can autonomously search and identify underwater UXO on a 250 pound platform.

SUMMARY:

The DOD EOD Program covers a broad spectrum of technology areas that address the issues of detecting, accessing, identifying, rendering safe and disposing of UXO. The use of field input for needs in the form of NCPs along with the coordination of technology with the military user community ensures that the scant resources available to the JSEOD program are properly applied. The identification of major mission areas along with alignment of 6.2, 6.3, MFP-11, 6.4 and congressionally mandated funding ensures that money is spent wisely and that the user sees a final transition to a fielded tool. The format of the road maps also allows other technology communities to quickly identify areas where their technology can be leveraged to shorten fielding time or reduce program cost. A coordinated approach such as this for the UXO community would provide similar benefits and allow commercial vendors to more efficiently apply their technologies.

UXO INVESTIGATIONS IN THE LIMESTONE HILLS, MONTANA

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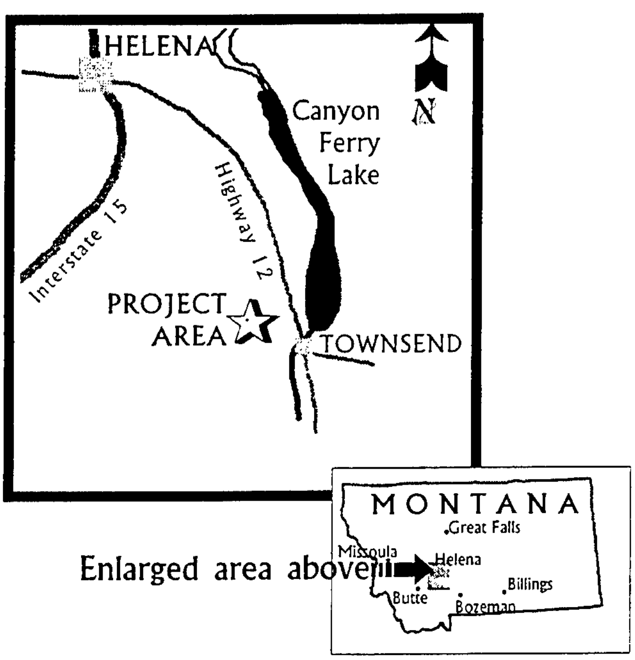
ABSTRACT

Past actions by the Montana Army National Guard (MT ARNG) contaminated Bureau of Land Management (BLM) land in the Limestone Hills, Montana (Figure 1) with unexploded ordnance (UXO). A limestone quarry and lime plant owned and operated by Continental Lime, Inc. (CLI) of Salt Lake City, Utah was prohibited from expansion of their quarry operation and hence faced loss of vital ore reserves due to danger from UXO. The MT ARNG was faced with quantifying the UXO danger with limited funding and resources while under the double threat of litigation from CLI and revocation of its lease with the BLM. An emergency closure of several thousand acres of public land was implemented by the BLM until UXO danger could be adequately addressed. This closure was highly unpopular with the recreating public, further leading to adverse publicity. This paper describes actions taken by the MT ARNG to preclude litigation and retain continued use of the Limestone Hills for training. A stratified random sampling protocol employed during magnetometer surveys is discussed. Performance of MK 26 and MK 29 detectors is discussed relative to geophysical conditions on site. Constraints associated with UXO assessment on public land when contamination stems from the National Guard versus active component forces are discussed. Recommendations are made with respect to minimizing logistical and technical obstacles in conducting future UXO investigations in the Limestone Hills.

FIGURE 1. General location of project



INTRODUCTION

Problem Statement

Unexploded ordnance poses a serious safety problem as well as a potentially enormous liability when present on public land. Determination of potential risk from UXO on public land is complex and costly. It is also beyond the routine technical capabilities of most state militias. When UXO contamination stems from National Guard rather than active component training, assessment and remediation become primarily a state responsibility.

Federal funds may not be available to support UXO assessments by states. Public lands used only by the Guard for training are not considered as Formerly Used Defense Sites. Nor are such sites likely to receive Defense Environmental Restoration Program (DERP) funds except in the most extreme cases. DERP funds are restricted to sites where "an imminent threat" is assigned by DoD through a qualitative (versus quantitative) process. The process effectively "screens out" sites not meeting stringent risk criteria, leaving sites with "lesser" or "unquantified" UXO risk unfunded. Initial site characterization costs routinely exceed $2,000/acre when contracting through Army Corps of Engineers. Consequently state militia's may be unable to sup-

port independent assessments of UXO-contaminated land.

DoD regulations on UXO assessment and remediation may conflict with statutes governing public land. While DoD remains a responsible party with respect to liability, it has no real authority regarding management of UXO-contaminated public land unless a land withdrawal occurs.

Conflicts between existing users of the public land may add a layer of complexity to the problem of UXO assessment and remediation. Discovery of UXO on public land typically precludes other legitimate uses of the site. Closures of public land are highly unpopular and potentially costly if existing users are prevented from proceeding with permitted enterprises - such as mining. Litigation is likely unless obvious progress in assessment and remediation is demonstrated. The economic impact on a rural community resulting from closure of a large mine is potentially devastating. Political pressure to quickly resolve UXO issues can result in hasty or incomplete analysis. A decision to tackle the problem with in-house resources further limits access to DoD experts and Army UXO assessment expertise while simultaneously increasing state liability.

Site Description

The Limestone Hills Training Area is located in the foothill region of the east slope of the Elkhorn Mountains, approximately 30 miles south and east of Helena (Figure 1). The area under consideration for mine expansion is located at the north end of a feature labeled "Limestone Hills" on the Townsend United States Geological Survey (USGS) 15-minute series map (Figure 2).

The terrain is rugged, with massive limestone outcrops forming pediment spur ridges, interspersed with terraces, fans and foot hill slopes. Active quarrying operations are located five miles west of Townsend, MT in Section 33, T. 7 N. R. 1 E. in Broadwater County. UXO investigations were conducted immediately south of the existing mine permit boundary of the Indian Creek Mine of Continental Lime, Inc and proceeded south down the crest of the ridge line.

Geologic conditions in the Limestone Hills are complex, and consist of an extensive sequence of limestones, quartzites, and shales overlain and intruded by younger, iron-rich volcanic materials. The contact zone between the sedimentary and volcanic rocks is rich with metallic mineralization. In the study area, bedrock is overlain by discontinuous soils of variable depths. Exploration work completed by CLI indicates that the soils range from 6 inches to 75 inches in depth.

The massive limestone ridge on which mining occurs forms a natural barrier on the west side of the live-fire operations in the adjacent valley. The series of rock walls, cliffs and terraces associated with this massive ridge rise nearly vertically from the valley floor. Elevations rise from 4,800 to 5,800 feet MSL at the highest portion of the ridge line. This ridge line is the principal physiographic feature of the area and it trends southerly for approximately 7,500 meters. Live-fire training has historically occurred in the valley floor and presently continues under a right-of-way lease agreement with the BLM.

History

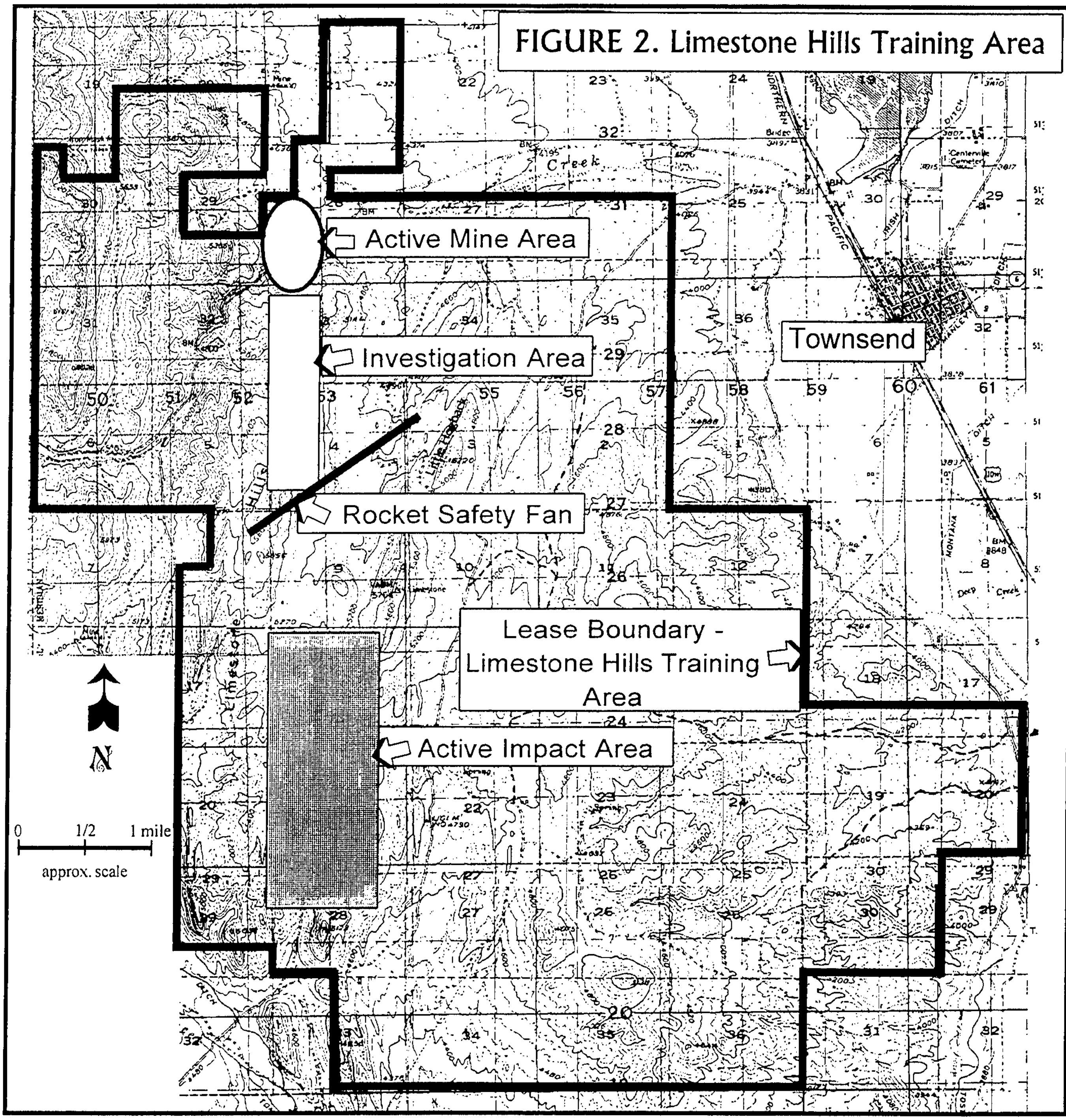
The Montana Army National Guard (MT ARNG) has used the area known as Limestone Hills Training Area since the 1950s. The training site has been used for maneuver and live-fire training for Infantry, Armor, Artillery, Engineer, Aviation, and Special Operations units during the ensuing years. In the past, all areas of the training site were potentially open as impact areas and live-fire ranges. The area proposed for mine expansion is outside the surface danger zone for all weapons currently in use by the MT ARNG. There are no historical records of the survey site serving as an impact area and there is no direct evidence of the area ever having received other than ricochets of inert (training) rounds.

Mining Operations

The Continental Lime, Inc. (CLI) Indian Creek Plant is located at the northern end of the ridge (Figure 2). CLI mines high quality calcium carbonate (limestone) from a thick massive bed of uniquely pure limestone. Mining is accomplished using standard open pit and quarry mining practices. Limestone is processed into quick lime at the Indian Creek Plant.

In 1992, CLI formally applied to the Montana Department of State Lands and the BLM for a life-of-mine permit. CLI's permit application sought approval to expand their existing operations down the entire ridge line. Such an expansion would have required the eventual cessation of live-fire operations by the MT ARNG once mining penetrated existing range safety fans.

After lengthy negotiations among the affected parties, the BLM determined that only the area north of MT ARNG's 2.75 inch rocket safety fan line would be considered for mining. This decision was based on the potential to adversely impact the MT ARNG and the fact that the area south of the 2.75 inch rocket safety fan line was known to be contaminated with UXO. The area north of the rocket



fan line would provide CLI with an additional twenty (20) years of proven limestone reserves.

PRELIMINARY UXO INVESTIGATIONS

Preliminary Assessment

In August of 1993, the Army Corps of Engineers Mandatory Center for Expertise of Huntsville, Alabama (HUNTSVILLE) supervised a Preliminary Assessment (PA) of four (4) areas within the MT ARNG right-of-way agreement for the presence of both unexploded ordnance (UXO) and ordnance and explosive waste (OEW). The PA determined that the area immediately south of CLI's existing mine permit was deserving of further site characterization due to the presence of shrapnel and inert tank rounds.

The results of the PA were briefed to the BLM and CLI.

The BLM responded by ordering an emergency closure of approximately 8,000 acres of public land. This closure occurred just prior to hunting season and was very unpopular with a large segment of the local Townsend community. A highly contentious public meeting was held to discuss the year-round emergency closure. Questions regarding MT ARNG's compliance with the conditions of the Right-of-Way Lease Agreement were voiced. The BLM promised to investigate the matter. The need to demonstrate progress in resolving the UXO problem was reinforced by this meeting.

Site Investigation

A Site Investigation (SI) was the next required step in the site characterization process. Discussions on how to proceed ensued with HUNTSVILLE. Defense Environmental Restoration Program (DERP) funds were requested and some funds were received from the Army Environmental Center (AEC). A site visit by HUNTSVILLE occurred in late March. Three specialists in UXO assessment and remediation from HUNTSVILLE made up the visiting team. A tentative scope-of-work for the SI was agreed upon along with a tentative time table for execution. The SI would be contracted totally through HUNTSVILLE if sufficient funding could be obtained through AEC (DERP funds). Should the MT ARNG be unable to obtain the necessary funding, HUNTSVILLE agreed to provide technical oversight on an in-house effort. Additional funds were requested from Army Environmental Center (AEC).

A detailed draft scope-of-work for the SI was received from HUNTSVILLE in May 1994. The scope-of-work called for a surface sweep of the 10-year mine disturbance area (approximately 120 acres) for $254,021.

A decision by the Deputy Under-Secretary of Defense for Environmental Security froze DERP funds received by the MT ARNG for UXO work. These funds would remain unavailable pending a determination of the risk to human safety. Without DERP funds, the MT ARNG was unable to contract with HUNTSVILLE for completion of the SI by a contractor, however technical oversight was provided for an in-house surface sweep.

Site Investigation Methodology

Prior to surface sweeps on the site, ortho-photo coverage was obtained. The site was then partitioned into 100 x 100 meter grids (Figure 3). A transparent overlay of all grids was produced to the same scale as the ortho-photo and used to transpose grid corners onto a "blue line" map. Multiple maps were produced in this manner. The availability of these maps allowed survey crews to quickly locate grid corners during survey work. Without ortho-photo maps, it is doubtful the survey could have been completed in time to conduct the SI.

The surface sweep was accomplished using traditional guardsman and EOD personnel. Guardsmen served as "walkers." Twenty walkers and four EOD personnel swept each grid systematically by moving line abreast, at arm-length intervals. EOD specialists walked 10 meters behind the line at an interval which allowed supervision of five walkers per EOD specialist. Walkers were commanded by an NCO in the line. An additional four guardsmen were deployed in advance of the walkers to find grid corners. All walkers and survey teams were commanded by a second lieutenant.

Standard safety procedures were implemented. Walkers were instructed not to touch or pick up any objects encountered. EOD specialists were called forward for all suspected discoveries. The senior EOD team NCO had final say on all matters relating to safety. EOD teams were from the 53rd Ordnance Detachment, Yakima, WA and the 120th Fighter Intercepter Group, MT ANG.

Results of the Site Investigation

No UXO was located during the SI on the 205 acre survey site. No impact craters, blast "foot prints" or clear evidence of impact by high explosive (HE) rounds were discovered. Shrapnel was noted as present but not recorded by location or size or type in a systematic matter. The following inert rounds were discovered:

1 - 76mm AP
5 - 90mm AP
1 - 105mm Illumination
2 - 155mm Illumination

Originally, the SI was to have swept only the 120 acres within the 10-year mine plan. However, walkers were able to cover an additional 85 acres. This resulted in coverage of all surface area from the existing mine permit boundary to the 2.75 inch rocket safety fan line (Figure 2).

Site Risk Assessment by Army Safety

A site visit to the Limestone Hills by three Army safety specialists was made concurrently with the SI. The team was tasked by Army Safety to provide an assessment of the potential risk associated with UXO on the site. The team was made up of safety and EOD specialists from US Army Forces Command. The team determined that UXO con-

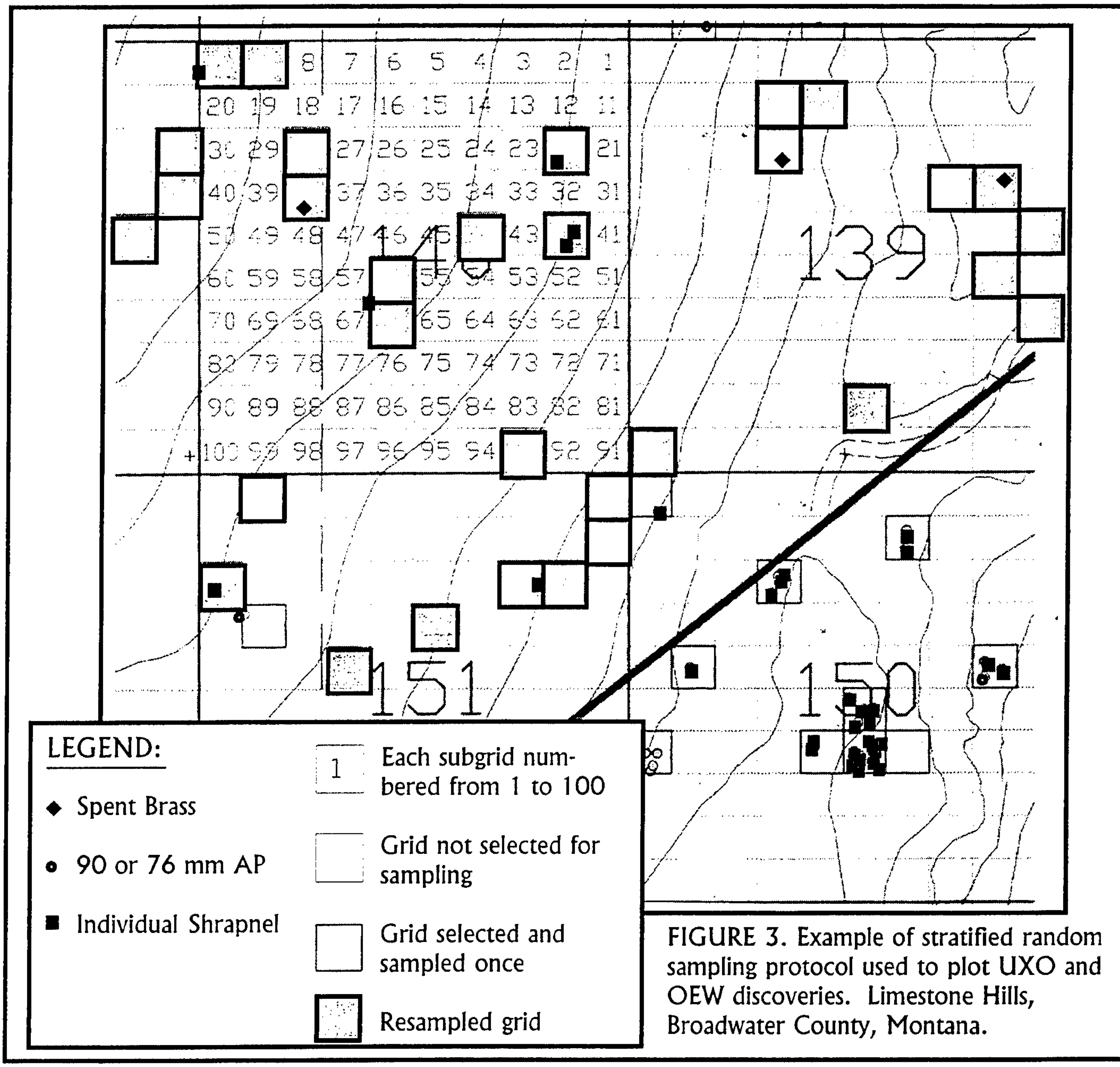


FIGURE 3. Example of stratified random sampling protocol used to plot UXO and OEW discoveries. Limestone Hills, Broadwater County, Montana.

tamination at Limestone Hills Training Range did not meet the RAC-1 or "imminent threat" criterion. Limestone Hills was given a RAC-2 classification with respect to risk.

SUBSURFACE INVESTIGATIONS

Defining the Scope

With the completion of the SI, HUNTSVILLE recommended that, as a minimum, a 10 percent subsurface sweep should be accomplished using magnetometers.

HUNTSVILLE was reluctant to provide technical oversight of "in-house" sub-surface surveys for UXO. The reason for this reluctance may have been based on past difficulty experienced in exercising adequate command and control over state guardsmen. When a civilian contractor is retained, command and control is not an issue because a contractual bond exists. Only if the MT ARNG could fund a magnetometer study through HUNTSVILLE to an approved contractor, would HUNTSVILLE remain involved with the project.

MT ARNG lacked sufficient funds to contract for magnetometer work through HUNTSVILLE, yet the requirement for subsurface investigations remained. The loss of supervision and technical oversight from HUNTSVILLE heightened concerns about the validity of in-house UXO subsur-

face investigations. Initially, it was proposed that EOD teams be brought in as funds allowed and given broad taskings to locate UXO in the area without "interference."

The merits of independent or "third-party" oversight were debated without consensus opinion. A majority opinion was that such oversight added unnecessarily to the complexity of the task. A minority opinion suggested that third-party technical oversight could help resolve many problems confronting EOD teams. The following points were made in support of independent technical oversight: 1) An understanding of the physics underlying the detection capabilities of the instrument could facilitate resolution of anomalous results in the field and help optimize use of the instrument, 2) The geologic complexity of the survey area could lead to a high degree of systematic "noise" that could result in serious, undetected sampling bias, 3) As complete coverage was not feasible, a sampling protocol would need to be implemented so as to allow for a valid statistical analyses of results, 4) Independent technical oversight could enhance quality assurance/quality control efforts and reduce the potential for results to be perceived by the public as "biased," 5) A technical report would be needed. This would be best accomplished using an independent contractor experienced in producing such reports.

Site Conditions and Equipment Evaluation

EOD personnel prepared to utilize both MK 26 magnetometers and MK 29 all-metals locators to sweep the site. The MK 26 is a flux-gate gradiometric search instrument that measures changes in the earth's magnetic field caused by iron-rich materials in the subsurface. The MK 29 all-metals locator is a frequency-domain electromagnetic induction instrument that can identify electrically conductive materials in the subsurface. Both instruments have been designed specifically for military use, are based on proven technology, and are extremely easy to use.

The key to a successful UXO investigation is proper planning. This includes a thorough understanding of the equipment and its limitations. A basic understanding of sampling theory and statistical methods are necessary to adequately design a sampling protocol.

Pilot Tests

To assess the effectiveness of magnetometers at the site, a pilot test was completed. Inert ordnance and ferrous objects of various sizes were buried at known depths in a test plot near the survey area. EOD personnel then swept the test plot with both MK 26 magnetometers and MK 29 all-metal locators. The pilot study helped assess the accuracy of detection equipment under site-specific conditions at Limestone Hills.

As a result of the pilot test, background interference from geologic conditions and depth of detection limitations for the instruments were determined. A 40 mm round buried at one foot depth was not detected by the MK 26 magnetometer because of varying amounts of iron-rich mineralization in the limestone deposits. A 155 mm round buried at 5 feet depth could not be detected by the MK 29 all-metals locator because it was deeper than the detection capabilities of the instrument. Thus, third-party oversight by a geophysicist allowed on-site evaluation of unusual instrument response.

Sampling Design

A sample design plan was proposed prior to initiating further work (Figure 3). The basic sample unit would be a sub-grid of 10 meters on each side. Thus, within each major grid there existed 100 sub-grids. In order to ensure each major grid was adequately sampled, a stratified random sample design was selected. This sampling design ensured that every major grid on the site would be sampled at the same level. Had selection of sample grids been completely random, large gaps in sample coverage could have occurred from chance alone. Selection of sub-grids was accomplished using a random number generator. Due to the additional time and effort required to locate sub-grids, it was suggested that only the intersections (corners) of major grids be sampled. This approach would have eliminated the need for additional survey work. However, selecting sample grids in such a manner would violate the assumption of independence of errors and preclude a meaningful statistical analysis of the data.

Sub-grids were located by survey teams in advance of magnetometer teams. Delineation of sub-grids onto ortho-photos facilitated survey efforts. Wooden stakes were used to mark the center of sub-grids.

Data Management

A standardized method of recording data was needed as well as a method of tracking the status of the magnetometer survey on a daily basis. The total population of sub-grids on the survey area was 5,512. If 10% of the total population of sub-grids were sampled, results from over 550 individual sub-grids would have to be recorded, tracked and ultimately analyzed.

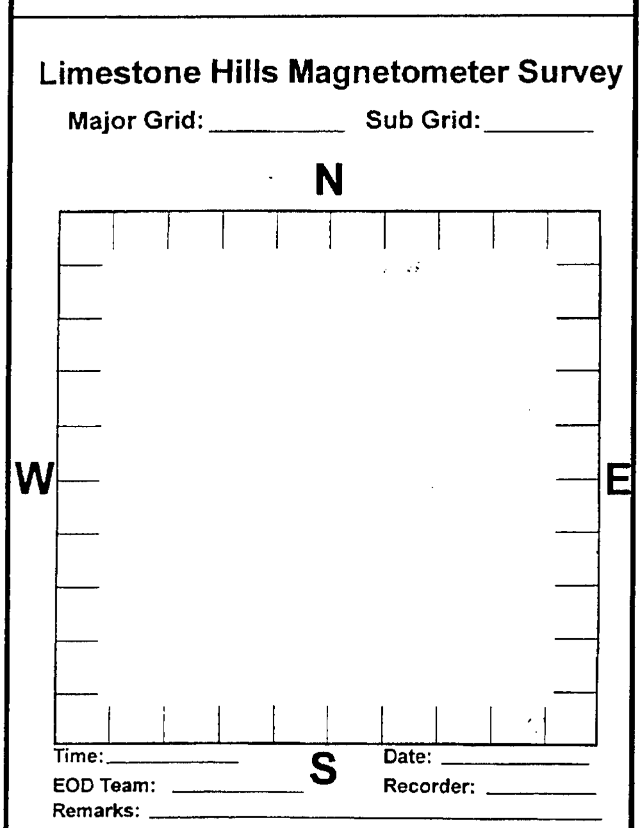
A master "status map" was created to track the progress of the magnetometer survey. The status map was created from a Computer Assisted Design (CAD) plot which delineated

all grids and sub-grids on the site (Figure 3). Major grids were sequentially numbered, sub-grids were nested sequentially within grids and numbered systematically from 1 to 100. The numbering sequence was standardized across all grids, facilitating rapid location of the sub-grids on the status map.

To facilitate tracking of results, EOD teams were each assigned a color code (Red Team, Blue Team, etc.). This color-coded approach allowed for a simplified visual tracking on the master status map. By using colored markers which corresponded to the respective EOD team, individual team progress as well as total progress could be readily determined by the project leaders.

Standardized data sheets were created to ensure results were recorded in a uniform manner (Figure 4). The data sheet featured a schematic of a sub-grid with incremented tic marks along all sides of the grid. Tic marks facilitated accurate plotting of discoveries. Each EOD team was assigned a recorder. Time, date, and EOD team were recorded. All discoveries were plotted onto the grid schematic accompanied by descriptions of the discovery. Anomalous readings were also noted on the schematic as were equipment problems. Data sheets were collected daily at Training Site Headquarters and reviewed for completeness. The master status map was updated.

FIGURE 4. Example of sampling grid.



QUALITY ASSURANCE/ QUALITY CONTROL

Defining Quality

During the planning phase of the magnetometer survey, it was recognized that measures to control the "quality" of the survey should be implemented. The survey would use EOD teams from different component commands. Teams would be using different types of detection equipment under highly variable weather, terrain and geophysical conditions. Serious sampling bias was likely without quality assurance/ quality control measures. We defined the "quality" of the magnetometer survey as being composed of two components: 1) survey precision and 2) survey accuracy.

Precision

We defined precision to mean the "repeatability" of a measurement result. For example, if two different EOD teams using the same equipment obtained different results on the same sample grid, precision would be low. If one EOD team consistently found less than another team, then a systematic error in the sampling was present (i.e. sampling bias was high). Random error can be dealt with without serious consequence to the validity of the finding in statistics; systematic error cannot.

In order to check for possible systematic errors in sampling, one out of every ten sub-grids surveyed was resampled by a different EOD team. Because the site was previously surveyed (and all shrapnel or metallic objects collected), the re-sampling could not be considered as a means to directly measure "precision." However, the resampling did have the potential to discover any buried objects which had been missed by the first EOD team. If the re-sampled sub-grids failed to reveal additional finds, sampling bias due to equipment or human factors could be considered low.

Accuracy

Accuracy was recognized as the other component of "quality." We defined a measurement result to be "accurate" when it closely agreed with the true parameter. Arriving at an estimation of accuracy in the field is clearly difficult. In geophysical work, a test pit may be excavated after a magnetometer survey. The location of all ferrous objects are then plotted and compared to the magnetometer results.

Thus, the accuracy of the equipment can be directly obtained.

The remoteness of the site, the mountainous terrain and a host of environmental constraints precluded use of test pits. Thus, only the test plots with known buried objects could be used to estimate accuracy. Each EOD team was required to demonstrate detection capability on the test plot prior to working on the actual site. This admittedly primitive approach had, at a minimum, the ability to determine if equipment was calibrated properly and generating signal responses consistent with previous trial results.

The Magnetometer work was initiated in October using Active, Reserve and Guard component EOD teams equipped with MK 26 magnetometers and MK 29 all-metals detectors. Anomalous readings were investigated by the geophysicist. Limited funds precluded the geophysicist from being on site throughout the survey. Thus, each data-sheet which identified either an anomalous or unresolved "hit" was segregated for re-sampling in the presence of the geophysicist during a subsequent site visit.

RESULTS

As would be expected, the use of magnetometers to clear such rugged terrain was extremely tedious and slow. On open ground with gentle terrain, ten (10) sub-grids could be swept in one hour. Under steep terrain conditions with moderate to thick vegetation, clearance rate decreased to five (5) sub-grids per hour per EOD team.

The logistical obstacles entailed in supporting a magnetometer sweep of so many sub-grids are obvious. However, most of the objectives of the magnetometer survey were accomplished. EOD teams using MK 29 all metals detectors swept several dozen sub-grids with soil depths that exceeded the detection capability of the equipment. These sites had to be re-sampled with MK 26 magnetometers.

Twelve percent (673 of 5,512 sub-grids) of the total surface area was surveyed for buried UXO with either a MK 26 or MK 29. Most QA/QC was accomplished on sites where anomalous readings were encountered or where data sheets were missing or incomplete. Nearly 100 additional sub-grids had to be surveyed in the Spring of 1995 to resolve anomalous readings.

Approximately 30% of all sub-grids contained at least one piece of shrapnel. No UXO was discovered on any sub-grid. Several 76 mm and 90 mm AP rounds were found. These rounds appeared to be ricochets from old tank hulls used as targets in the valley below the ridge line. The pattern of shrapnel distribution was consistent with the hypothesis that the area had not been directly impacted with high explosive ordnance. Shrapnel frequency was highest along the crest of the ridge. Shrapnel frequency dropped off sharply on the back side of the ridge line, suggesting the ridge line intercepted most fragments. Exit briefs of EOD teams were conducted. No impact craters, blast "foot prints" or other indications of direct impacts from explosive ordnance were detected. All data sheets, maps, note books and relevant correspondence were turned over to the MT ARNG State Safety Officer for review. The geophysicist's report along with all after-action reports were also provided to the Safety Officer for review.

DISCUSSION

EOD teams performed with competence and exceptional spirit. Within the MT ARNG, logistics support and command and control were problem areas. Such problems are unavoidable when funding is limited, time-lines are constricted, and the sole qualification for participation in the project is availability. "Skill matching" is critical to a successful outcome of such a complex effort.

The importance of senior command involvement on a daily basis in such complex projects cannot be understated. Absent such senior leadership, junior officers were left to decide on how to allocate limited resources among competing needs. Too often, critical resources were diverted or delayed from the project without command-level knowledge.

The role of civilian specialists must be clearly defined. Absent clearly defined roles and responsibilities, civilians may be placed in awkward and untenable roles. While civilian participation is critical at the planning level and in an oversight capacity, execution of the operational plan properly lies with military personnel.

The roles and responsibilities of the Safety Officer in UXO investigations should be clearly defined. Daily involvement by the Safety Officer in reviewing results, methods or problems would facilitate resolution of conflicts and provide a direct link to command-level cadre.

The MK 26 magnetometers and MK 29 all-metals locators were found to be excellent instruments for the project. The in-field response of the instruments to subsurface materials allowed quick assessment of suspect targets. This real-time response is not possible with other types of geophysical instruments, such as proton precession magnetometers which are widely used by civilian consultants

The real-time response of the instruments can cause a false sense of security. Background geologic noise causes EOD

operators to adjust the range of the instrument's audible output, and as a result, reduce detection sensitivity. Therefore, attention must be directed to monitoring these adjustments and understanding their impacts on detection capability.

A thorough understanding of EOD search equipment and its limitations is essential. A major shortcoming in using these instruments is that no permanent record of the magnetic and electromagnetic field values are collected. Thus, the success of the entire investigation is dependent on EOD personnel field procedures.

Instrument use must also be consistent with geologic conditions. Combined use of the MK 26 magnetometers and MK 29 all-metals locators allowed for a more thorough screening of the area. Single instrument response was complicated by complex geologic conditions. Therefore, complementary output from the instruments reduced the confounding influence of mineralization and soil depths.

CONCLUSIONS

On land where mining is planned to occur, an appreciation of the detection limitations of magnetometers is essential. In our experience, UXO detection capability was routinely assumed to be greater than site specific conditions allowed. The detection capability of EOD equipment varied widely depending on the geology of the site. The influence of geophysical conditions on detection capability must be considered and incorporated into the final report. The decision to permit an activity on public land ultimately rests with the land management agency, not the state or DoD. The decision-maker must understand that magnetometer results can and do vary widely in detection performance. Unjustified confidence in results may result in decisions with tragic consequences.

The problems associated with conducting UXO investigations with limited in-house resources are serious. The difficulties encountered stem largely from the enormous disparity between executing a military operation and conducting a scientific assessment. The problems encountered in this investigation were, in retrospect, to be expected. Without technical oversight and a standardized, systems approach to UXO investigations, state militias will continue to struggle to resolve the problem of UXO contamination with mixed results. Hopefully, the lessons learned in the Limestone Hills will prove helpful in planning UXO investigations with limited resources and limited DoD support.

UNEXPLODED ORDNANCE REMEDIATION AT THE UMATILLA CHEMICAL DEPOT

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INTRODUCTION

The Umatilla Chemical Depot (UCD) was required to address the relationship of an Unexploded Ordnance (UXO) cleanup to Base Realignment and Closure goals, Army policy, and the environmental laws at a time when such relationships were (and still are) being addressed nationwide by policy makers. Decisions at UCD were made in accordance with existing laws and policies, and the surface clearance portion of the cleanup action was initiated and is ongoing. A decision on the final extent of the subsurface ordnance removal was deferred until future land use is known. Additional data obtained during the ongoing cleanup may show that subsurface clearance is prohibitively costly and may require adjusting the additional planned actions to match available funding. The following is a case study of the UCD project related to ordnance clearance.

BACKGROUND

The Umatilla Chemical Depot (UCD) (formerly Umatilla Depot Activity) is a 20,000 acre Army facility established in 1941 in rural northeast Oregon. It formerly operated as an ammunition depot, performing both conventional and chemical ammunition storage and conventional munitions refurbishment and disposal functions.

UCD was placed on the Base Realignment and Closure (BRAC) list in 1988. Although the presence of its chemical mission prevented closing of the post within the time frame of the BRAC law, UCD was required to transfer all of its conventional ammunition mission to another post in preparation for the eventual end of the chemical mission as part of the Chemical Stockpile Demilitarization Program.

As part of its past munitions refurbishment activities, UCD operated a washout plant from which explosives-contaminated wastewater was disposed of into nearby leaching lagoons. This disposal created an onpost groundwater plume in an aquifer that is extensively used for agricultural irrigation just off UCD. Primarily due to this, UCD was placed on the National Priorities List (NPL) of uncontrolled hazardous waste sites. Another area affected by the mission was the Ammunition Demolition Activity (ADA) Area, a 1750-acre area where open burning/open detonation (OB/OD) activities were carried out.

The major laws governing environmental work at UCD were the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). To implement these laws, a Federal Facility Agreement

(FFA) was signed with the U.S. Environmental Protection Agency (USEPA) and State of Oregon (State). The FFA included deadlines for the cleanup action which were enforceable by monetary penalties.

Prior to the NPL listing, the Army had been conducting environmental studies throughout UCD, including in the ADA Area. Following the BRAC listing, with its associated possibility of unrestricted release of the UCD property, an exhaustive search was conducted for all sites of environmental significance. The FFA governed the work at all of these sites.

REMEDIAL INVESTIGATION

The Remedial Investigation (RI) under CERCLA was intended to define the nature and extent of environmental contamination throughout UCD. As one of the major use areas of UCD, the ADA Area was determined through records searches and aerial photographic analyses to contain numerous locations with possible contamination (see figure 1). A large part of the area was known to have hosted OB/OD operations in the past, and such operations were still ongoing in certain areas. Aerial photography indicated large areas of former pits where previous ordnance destruction/disposal may have taken place. Interviews with various former and current depot personnel identified several instances of undetonated surface ordnance being found, including large bombs. The conclusion reached from this information was that ordnance-related debris, and unexploded ordnance, had the highest probability of being located throughout the center of the ADA, however, any part of the ADA had some reasonable possibility of containing such debris and ordnance.

The areas with the highest certainty of past use, and those having had the most such activity, were candidates for sampling and analysis for soil and groundwater contaminants. Twenty areas were determined to have had enough previous activity that soil and groundwater contamination may have resulted, and sampling was performed at these sites (see Figure 1). Because of the UXO threat, any intrusive activities (i.e., vehicular access, ground disturbance) required ordnance clearance.

Such clearance was performed to a depth of 1-2 feet by contract/subcontract with Dames and Moore/UXB International. Access lanes were marked off with stakes and used to define safe areas during the various sampling episodes. The total area cleared and locations of items found were not recorded since the intent of this work was to allow the RI sampling to safety occur. During the clearance several hundred live ordnance items (see Table 1) were located and turned over to the depot for destruction.

Following the RI, a risk assessment was performed to determine whether cleanup was required for the soil and groundwater contamination. The risk assessment used standard procedures and assumptions published by the USEPA to determine soil intake, toxicity of contaminants, and resulting risk to current and future users. Five of the twenty RI sites were found to require cleanup to abate soil contamination from explosives, metals, and pesticides. The risk from ordnance was not described in the risk assessment, since the ordnance was considered an Army safety issue addressed by Army regulations. Also, procedures for determining a numerical estimate of such ordnance risk were not known.

FEASIBILITY STUDY

The Feasibility Study (FS) compared the relative advantages and disadvantages of various alternatives (see Table 2) for reducing the risk from the contamination in the five sites in the ADA. The alternatives involved access to, and soil removal from, the sites, hence UXO clearance would be needed prior to conducting the remedial action. Since the cost of this clearance is part of the remedy, and the FS requires describing all of the costs, the UXO costs were included in each alternative.

During review of the FS, the USEPA and State noted the hazard existing for persons accessing the ADA, and requested that ADA-wide clearance be included in the FS alternatives. The regulators felt that these hazards were within the jurisdiction of CERCLA to abate. The Army did not agree, but due to the possible future uses of UCD under BRAC, felt that such costs had to be addressed prior to selecting these future uses. Hence, ADA-wide UXO clearance costs were included within the Feasibility Study.

Concurrently with the FS, a State-appointed committee funded by the Department of Defense (DoD) was developing options for future use of UCD in coordination with the local public and the UCD. The future use limitations of the ADA area were considered in this process. A small part of the ADA area was then being used infrequently by the Oregon National Guard (ONG) for small arms practice, and a likely future use was considered to be continued training in the ADA area by the ONG. It was hoped that such use would preclude having to perform significant ordnance cleanup, since the usage would remain military.

Based on this likely use, a land reuse report was finalized

(Benkendorf, 1993). Later discussions with the ONG found that they planned to expand their use of the area to be more intensive, perhaps for armored vehicles . If surface access on foot or by vehicle was contemplated, then some area-wide ordnance clearance would be needed. Hence, the comparison of the various clearance options in the FS was still essential, even after our range of future uses was potentially limited to the ONG by the reuse task force planning.

Another complicating factor in the Army's discussions with the EPA and State was the publishing, in November 1993, of the Army's Interim Policy and Guidance on the Application of RCRA Hazardous Waste Management Requirements to Conventional Explosives Ordnance Operations. Such guidance continued the policy that ordnance used for its intended purpose was exempt from RCRA, but it indicated that disposal of ordnance was a RCRA-regulated activity. Clearly the ordnance at UCD had been disposed of. It seemed likely that Federal policy was moving in the direction of greater RCRA control over ordnance disposal, and CERCLA jurisdiction over ordnance disposed of many years previous.

The Army had major concerns with beginning the CERCLA process for UXO during the FS stage. Primarily, there had been no site characterization for UXO. The safety clearance had been performed, but not to more than 2 feet deep, only over a small area, and without a separate record of costs and area cleared. The CERCLA RI/FS process requires defining the nature and extent of contamination before making decisions for the level of cleanup. UXO was not addressed in the RI, which had already been finalized with the approval of the USEPA and State.

Besides actual live UXO, we were concerned that a great deal of metallic debris, both ordnance- and nonordnance-related, had been disposed of within the ADA. The ADA was known to have hosted a great deal of open burning and disposal of various scrap materials with metal components, including ammunition boxes, pallets, crates, rocket tubes, etc. Any search for UXO would have to be preceded by a complete removal of such metallic debris. The various ordnance search instruments would pick up this mostly ferrous material as well as ordnance. The ordnance disposal effort over the previous 50 years also generated a vast number of metal fragments that also would have to be removed during the search for actual ordnance.

The ability to distinguish small metal scrap from ordnance was investigated, but this ability was thought to be limited by the fact that a large variety of ordnance items (see Table 1) were disposed of including large projectiles, bombs, small mines, small arms ammunition, and fuses. We could not target one type of ordnance item with one type of magnetic signature.

Also, ordnance was scattered over a large depth range. Recent standard practice at UCD for OD operations was to bury a quantity of items 10-20 feet deep, and detonate it. This practice may have occurred over the large pitted areas that were noted on aerial photographs. Hence ordnance to 20 feet deep was a possibility over most of the ADA. These operations also generated considerable "kickouts" that ended up on the surface or just below it. Also, the loose sandy soil and windy conditions at UCD cause elevation changes in ground surface of several feet over a period of a few years. Activities in the past may have used a different SOP than at present, and the ground surface from the 1940s-1950s may have changed significantly. The basic conclusion was that live ordnance could potentially be found over most of the area, and at any depth to 20 feet.

Of the extremely large number of metallic "hits" we might find, and have to remove, perhaps less than 1% would be distinguishable as ordnance items, either live or dead. Note that removal of any item distinguishable as ordnance was considered necessary, since the finding of such objects by future non-Army property users would probably require the same response from the Army. We also had not conducted any type of risk analysis for UXO. We had located standard clearance depth ranges suggested by the U.S. Navy, and included them in the FS.

Despite these uncertainties and data gaps, we still had short FFA deadlines for completing the Feasibility Study and reaching a cleanup decision for UCD. A reasonable compromise had to be worked out for the UXO issue, that did not negatively affect the DA policy changes being negotiated for the same issue.

Despite these concerns, cost estimates for various depths of ADA-wide clearance were performed (see Table 2). The Army's contractor located a cost model from the Dept. of the Navy, and made assumptions for using the model appropriate to UCD. These included the number of items requiring excavation at various depths and the amount of effort required to remove each item.

Such cost estimates would be needed for the Army's decision about level of cleanup and its effect on future use of the property, regardless of whether UXO fell within the jurisdiction of RCRA and CERCLA. Cost of cleanup and future use possibilities had to be considered simultaneously: future use was determined by how much

cleanup could be accomplished, and future use could be restricted if adequate cleanup was not considered feasible and cost effective. Costs were developed for a range of clearance options that would allow a range of future uses including military, recreational, light industrial, and unrestricted. Costs are shown in Table 2, and range from $1.2M for surface clearance to $900M for complete removal.

EPA expressed some concern that due to the lack of information, the costs may have been estimated too high for the 1 foot and 5 foot clearance options, and would bias us more toward a land use restriction and less active cleanup. The Army had the opposite concern, that estimates may have been much too low.

We collected cost data from various projects and presented them (see Figure 2) to determine the adequacy of the UCD model estimates. This was intended as a rough check on the UCD estimates, and did not consider the cost impacts of site-specific details such as whether UXO anomalies were entered in a database, or whether a remotely operated magnetometer was used. Rather, we used the total cost of various projects divided by the number of acres cleared, and plotted this against the overall clearance depth that the project achieved.

It appeared the UCD model estimates were reasonable compared to other sites for the shallower clearance, say up to 1-2 feet. However, the lack of data at greater depths like 5 feet did not permit a good comparison. This certainly indicated that the estimates were not excessively conservative. In fact, we continued to have concern that our estimates were too low due to the uncertainties of the UCD site and the amount of metallic debris here.

PROPOSED PLAN/RECORD OF DECISION

The Army prepared a Proposed Plan under CERCLA that proposed a cleanup remedy that included site-wide ordnance clearance in order to comply with Army safety regulations. In discussions with the EPA and State, it was agreed that future use would dictate how much clearance was eventually required. Such an approach satisfied the Army's safety responsibilities, and also complied with the requirements for protection of human health and the environment that would exist for a CERCLA cleanup.

To retain some flexibility in choosing such clearance and to obtain more data to assist such a decision, we proposed a two-part remedy. Part one required a site-wide surface clearance of UXO. It was known that ordnance was lying on the surface in certain areas, and large parts of the 1750-acre ADA area had not yet been inspected. Any future use was expected to be more intensive than the current OB/OD use in which access was restricted to only the cleared roads. Hence, surface clearance was needed. The five sites requiring soil cleanup would also have to be cleared to the depth needed to accomplish the soil excavation. During each of these activities , the Army would collect the information on number, types, and depths of UXO found. This would be used to refine the cost estimates from the FS.

Future clearance would be selected from a series of ranges (see Table 3), after future use was decided by the Amy in coordination with the State and EPA. This proposed remedy was put out to the public for review as required by CERCLA, and there were no significant comments. It was finalized in a Record of Decision completed within the deadlines required by the Federal Facility Agreement.

REMEDIAL DESIGN

Remedial design was conducted to implement the remedy in the ROD. A design contract was awarded by the Army Corps of Engineers, Seattle District. The design contractor prepared the design in the format of a contract specification for the actual cleanup action, and in the format of the remedial action plans required to be submitted to the regulatory agencies under the FFA. A site plan safety submission was also prepared. The steps described in the design are shown in figure 3, and reflect the ROD except for the addition of a subsurface clearance over 10% of the ADA area. The 10% clearance would be conducted to a depth of 5 feet, and would allow us to record the number, types, and depth of the UXO. The total area to be surveyed/cleared would be distributed in grids throughout the ADA area to refine our estimates of the UXO density in both the heavily used, and unused, portions of the ADA area.

REMEDIAL ACTION

The work was started in early 1995 and is nearing completion. The surface clearance is being conducted by dividing the area into approximately 7500 100x100 foot grids. The grids are then walked by a team of UXO technicians holding magnetometers to verify the presence of metallic objects visible on the ground surface. Items that can be moved are collected in one area for detonation; items not able to be moved are detonated in place. In this dry area of the country, the UCD's fire protection service has been utilized several times to

extinguish fires caused by detonations.

Early concerns about UXO density and variety were supported by the results. Figure 4 shows that the majority of UXO items found were located in the middle of the ADA area in the most heavily used areas, but isolated findings of surface items occurred several thousand feet away from the known previous areas of disposal activity. These findings justified the complete surface clearance that was performed.

Approximately 4,000 items comprising over 100 types of ordnance were found in the surface clearance effort, as shown in Table 4. Most items were found from the surface to about 1.5 feet deep (Walenius, 1996), though UXO has been found up to 11 feet deep so far.

The five sites requiring soil cleanup were excavated with a backhoe and the soil was screened and inspected on a belt conveyor by UXO technicians. Found items were detonated; inert scrap was disposed of. As in the surface clearance, and number and variety of ordnance items found was large, as shown in Table 5. Over 40 types of ordnance totaling over 2700 items requiring detonation have been found thus far during the soil screening. Most of the items being recovered are inert scrap metal. Over 200,000 lbs of such scrap has been removed and disposed of so far at the ADA area.

CHANGES TO REGULATIONS THAT MAY AFFECT ACTION

Since the remedy selection was made on the UCD project, the munitions rule required by the Federal Facilities Compliance Act was proposed by USEPA in coordination with DoD. The UCD ADA area, as a past ordnance disposal area, is addressed in proposed section 40 CFR 261.2(g):

"Unused military munitions are discarded material and therefore a solid waste when any of the following occurs:

> (i) The munition is abandoned by being disposed of, burned, or incinerated, or treated prior to disposal...".

The proposed designation as a solid waste implies that disposed of ordnance may in the future come under the jurisdiction of a CERCLA-type cleanup. A Remedial Investigation and Risk Assessment would then have to be performed. In view of this, the work at UCD appears consistent with the future direction of waste UXO management activities.

CONCLUSIONS

The large amount, and fairly wide dispersal , of UXO on the surface of the UCD ADA area posed a concern for future use which is now being abated. The follow-on ADA-wide magnetometer survey and subsurface sampling will provide valuable data to refine the FS cost estimates for ADA-wide subsurface clearance. Such estimates will allow the Army, USEPA, State, and local community stakeholders in the future of UCD to make a more informed decision about the possible future of the ADA area and any additional UXO cleanup needed.

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DISCLAIMER

The thoughts and opinions expressed in this paper are those of the authors and do not necessarily reflect official Dept. of the Army policy and regulations. This paper presents preliminary results of remedial action work in progress. The results are as accurate as reasonable achievable now; the final results to be presented after project completion may differ slightly from the preliminary results here.

Table 1: Ordnance Items Located During the Remedial Investigation of the Umatilla Chemical Depot

ORDNANCE TYPE	AMOUNT
20mm Projectile	3
37mm Projectile	10
40mm Flare	Several hundred
57mm Projectile	2
60mm Mortar	1
75mm Projectile	7
81mm Mortar	5
105mm Projectile	2
2 inch Mortar	12
3.5 inch HEAT rocket	3
5 inch Barrage Rocket	1
Butterfly Bomblets	6
M56 point detonating fuse	3
Bomb boosters	6
Bomb fuses	4
Practice mine powder chrgs	9
Bulk HE pieces	9

Source: Dames and Moore, 1992

Table 2: Remedial Alternatives for the ADA Area of the Umatilla Chemical Activity

Soil Contamination Alternatives	Estimated Cost*
Soil cover on contaminated sites	$300,000
Excavation and solidification/disposal of soil	$2,400,000
Excavation and incineration and solidification of soil	$6,900,000
Offsite treatment and disposal of soil	$3,200,000

*Includes necessary UXO clearance at 5 soil excavation sites.

ADA-Wide (1750 acre) Unexploded Ordnance Clearance	Estimated Cost
Surface	$1,212,000
Surface and Subsurface to 1 foot deep	$7,225,000
Surface and Subsurface to 5 feet deep	$13,700,000
Surface and subsurface to 20 feet deep	$900,000,000

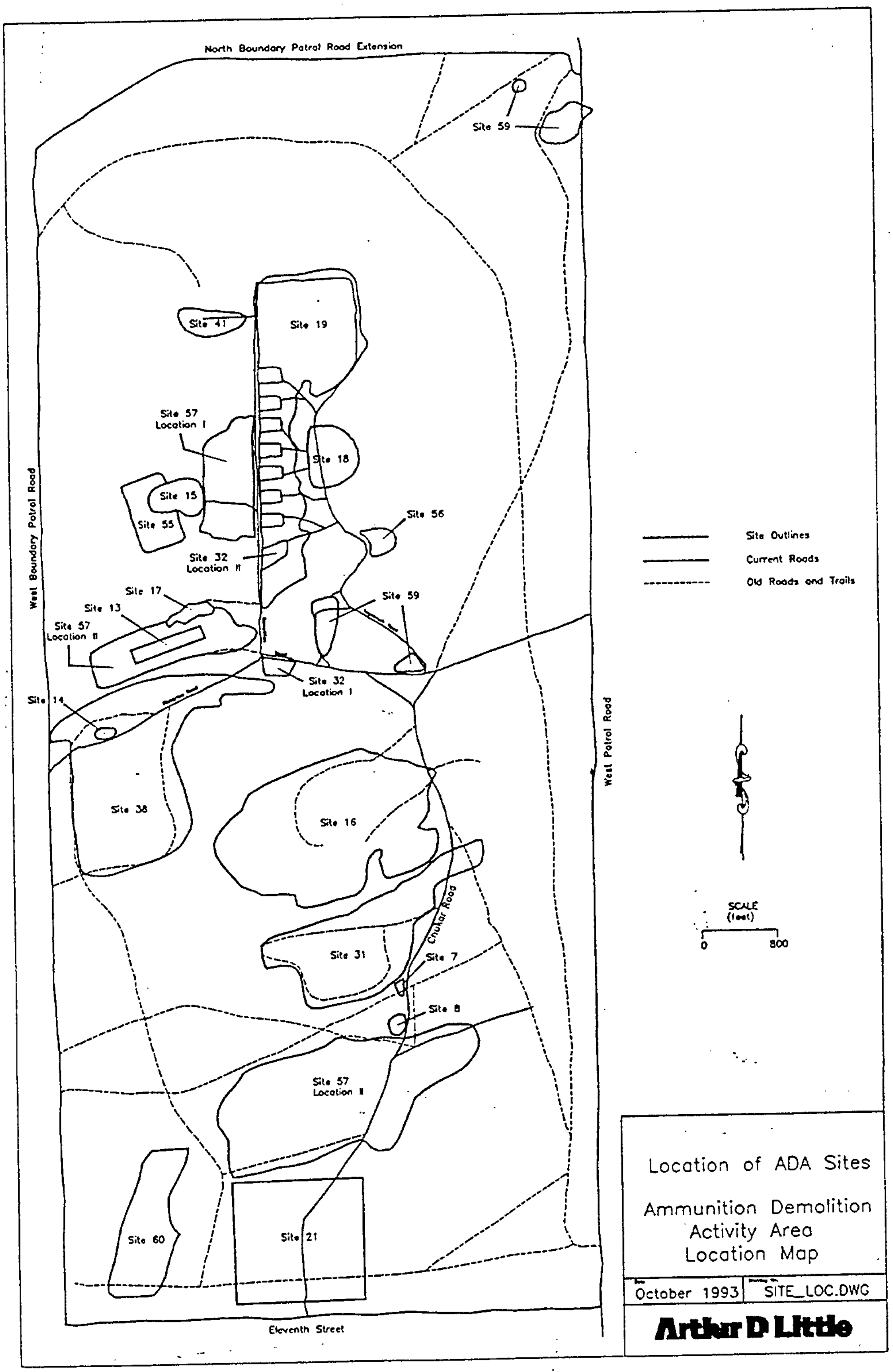
Source: Arthur D. Little, 1994b

Table 3: UXO Clearance/Future Use Options for Umatilla Chemical Depot

Land Use	Degree of Clearance
Current Army Use	Surface Clearance/Mag Survey
Recreational/Wildlife	Surface to 1 foot
Industrial	1 to 5 feet
Residential	5 to 20 feet

Source: Arthur D. Little, 1994a

Figure 1: Contamination sites in the Ammunition Demolition Activity Area of the Umatilla Chemical Depot



Source: Arthur D. Little, 1993

Figure 2: Per-acre costs for UXO clearance to different depths.

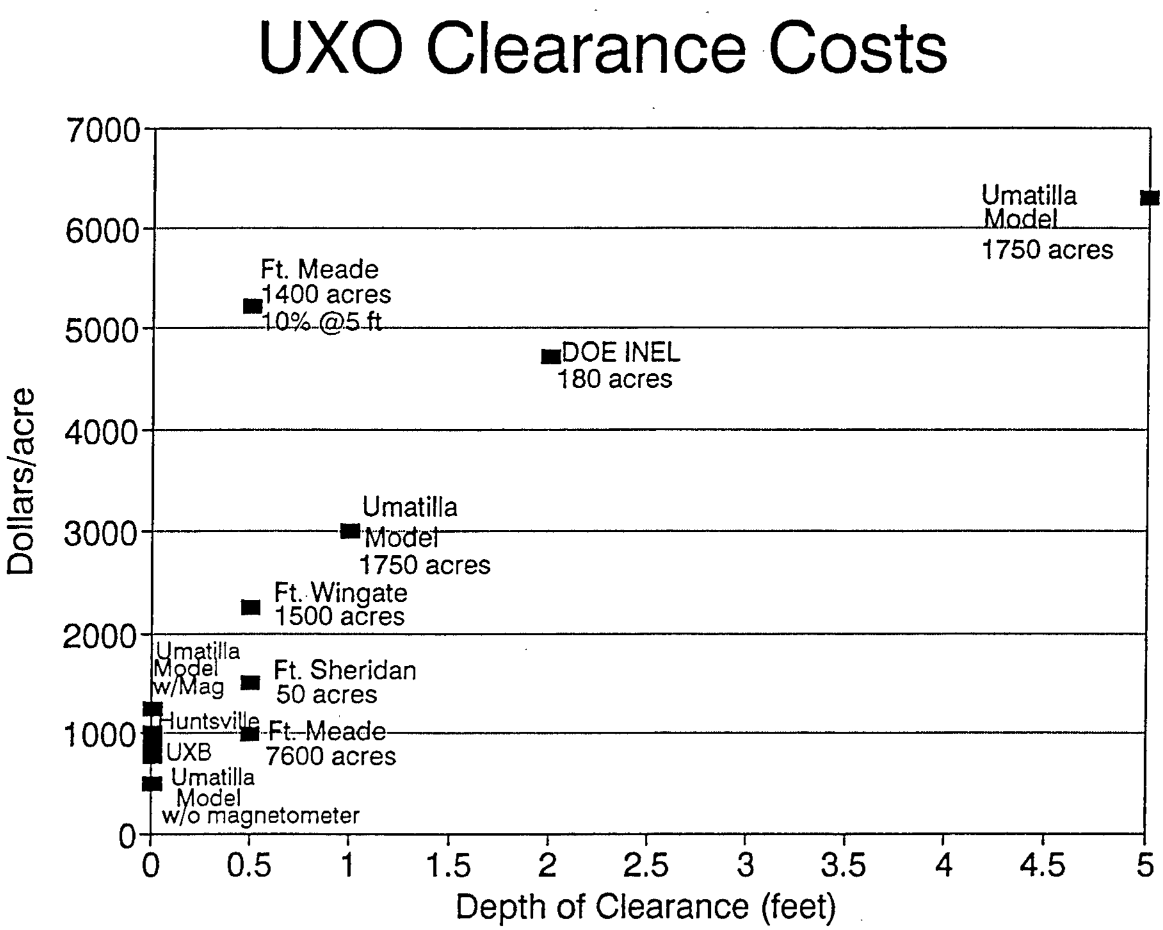


Figure 3: Remedial Design Steps for the Umatilla Chemical Depot

Perform surface clearance of the 1750 acre ADA.
Perform clearance to 5-10 feet at the 5 soil cleanup sites.
During clearance record locations and depths of objects found.
Clear 10% of ADA area to a depth of 5 feet and record depth, live/dead, ordnance related, etc.
Revise cost estimate
Note planned future use.
Note BRAC program funding constraints.
Revise remedy as necessary.

Figure 4: Locations of Found Surface Ordnance on Umatilla Chemical Depot's ADA Area Relative to Areas of Known Past Depot Activities (dots denote single UXO; solid squares = 5 or more UXO; outlines denote past activity areas)

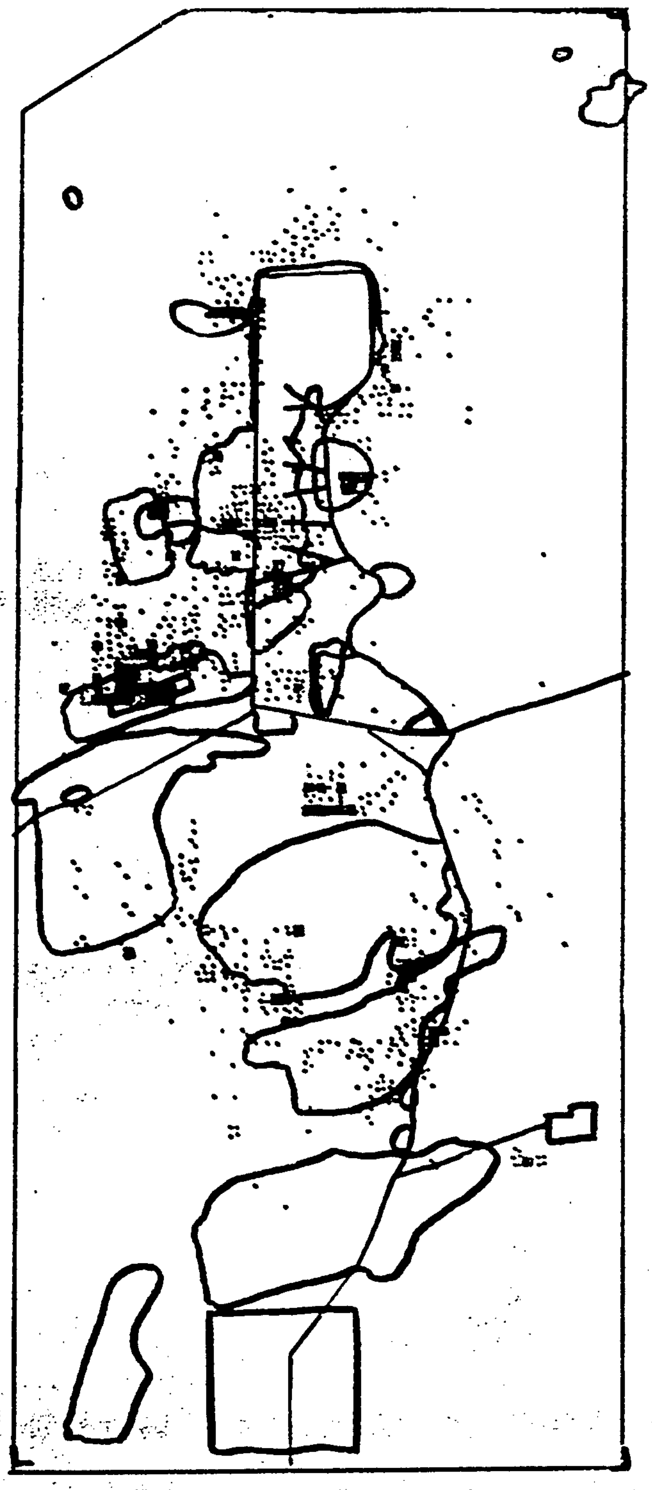


Table 4: Ordnance Found During ADA-Wide Surface Clearance and Soil Sifting of Five Sites at the Umatilla Chemical Depot

Ordnance Item	Sift Total*	Surface Total	ADA Total
105mm WP		2	2
106mm	2	0	2
2 inch rocket warhead		4	4
2.36 inch rocket (WP)		1	1
2.75 inch warhead	1	1	2
3.5 inch rocket warhead (HE)		3	3
3.5 inch warhead (WP)	3	1	4
ASST SMALL ARMS	1251	907	2158
Base Coupling		9	9
BD Fuse	20	11	31
Blasting cap		2	2
Bomb fuse, unk		3	3
Bomb, frag 20 lb		2	2
Bomb, frag 90 lb.		1	1
Booster, 3.5 inch rocket		12	12
Booster	42	31	73
Burster (unk)		4	4
Burster, 3.5 in. rocket (WP)	51	32	83
Burster, bomb		9	9
Detonator	13	12	25
Ejector, cartridge		2	2
Flare	2	7	9
Flare candle		12	12
Flare ignitor		5	5
Flare mix (loose oz.)		4	4
FMU-30B Fuse	1	1	2
FMU-74B Fuse		3	3
Fuse (unk)	11	21	32
Fuse Parts	1	24	25
Grenade Fuse	2	56	58
Grenade, MK2		1	1
HE (loose oz.)	7	201	208
M1 Adaptor		3	3
M100 Series Fuse	13	4	17
M112 Photoflash		1	1
M120 Fuse		3	3
M130 Fuse		3	3
M152 Fuse		1	1
M16 AP Mine		1	1
M161A1 BD Fuse	11	0	11
M1A1 Mine, AT		2	2
M2 Fuse Ignitor		1	1
M211 Fuse		3	3
M22 Photoflash		6	6
M31 (HE)	1	1	2
M401 BD Fuse		12	12
M402 VT Fuse		9	9
M404 BD Fuse	2	30	32
M43 MT Fuse	3	4	7
M48 Fuse		5	5
M48 Trip Flare		2	2
M509 Fuse		1	1
M51 Fuse		3	3
M52 PD Fuse	21	45	66
M524 PD Fuse	3	2	5
M525 PD Fuse		2	2
M54 Fuse		5	5
M56 PD Fuse	341	407	748
M565 MT Fuse		10	10
M57 Fuse		9	9
M603 Fuse		3	3
M77, PTTF		1	1
M83 (HE)	1	13	14
M88 Fuse	1	0	1
Mine Fuse		9	9
MK166 Fuse	4	33	37
Mortar, 60mm HE		2	2
Mortar, 81mm HE		24	24
Motor ignitor, 3.5 in. rocket		2	2
Motor, 3.5 in. rocket		1	1
MTSQ Fuse	1	41	42
PD Fuse (Unk)	7	22	29
Primers	29	651	680
Primer, M34		118	118
Projectile, 20mm HE	575	101	676
Projectile, 20mm Tracer	8	0	8
Projectile, 3 inch APHE		1	1
Projectile, 37mm APT		3	3
Projectile, 37mm HE	108	479	587
Projectile, 37mm Tracer	138	160	298
Projectile, 40mm HE		2	2
Projectile, 57mm APT	1	0	1
Projectile, 57mm HE		4	4
Projectile, 57mm HEAT		5	5
Projectile, 75mm HE	7	26	33
Projectile, 75mm WP	1	3	4
Projectile, 75mm WP burst		12	12
Projectile, 90mm HE	2	25	27
Projectile, 90mm Tracer		12	12
Propellant (loose oz.)		44	44
Rifle Grenade	1	23	24
Rifle Grenade Fuse	17	1	18
Rifle Signal Grenade		2	2
Rocket, 5 inch W/H		4	4
Smoke canister		2	2
Star signal		16	16
SUU-13 Eject. Cartr.		1	1
T-49 Fuse		2	2
T186 PD Fuse	25	73	98
T208 Fuse		1	1
Thermal Battery	3	9	12
Tracer	4	4	8
VT Fuse	2	4	6
TOTAL	2737	3898	6635

*As of February 1996

Time and Cost Benefits of an Archive Search Report

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INTRODUCTION

The purpose of this presentation is to provide a summary of one critical step in the Ordnance and Explosives (OE) program environmental response process. This step provides OE project managers with recommended response strategies and priorities that establish clear and defined subsequent contract actions. This step involves the use of experienced ordnance professionals reviewing historical records, performing site inspections and interviews, and evaluating ordnance usage data. The completed analyses are published in a site specific Archive Search Report (ASR).

These evaluations have been accomplished as part of the Defense Environmental Restoration Program, Formerly Used Defense Sites (DERP FUDS). All OE work has been performed under the direction of the Corps of Engineers' Huntsville Engineering and Support Center.

TECHNICAL OE TEAM

Experienced and qualified ordnance professionals should be the number one mark of performing first class ordnance evaluations. The OE team at the Rock Island District is comprised of Unexploded Ordnance (UXO) specialists who are former active duty EOD persons, Army ammunition specialists, archival record research specialists, chemical engineers, chemists, civil/environmental engineers, industrial hygienists and engineering technicians. There are more than 300 years of in-house technical ordnance experience that is available as each project is evaluated.

OE RESPONSE PROCESS

The OE response process starts with a Preliminary Assessment of the site to determine if the site is eligible under the DERP FUDS program. An Archive Search Report is tasked to the Rock Island District for select sites. If there is an imminent safety threat at any time during the response process, a Time Critical Removal Action (TCRA) for removal of immediate hazards within the site is initiated. For many sites, an Engineering Evaluation/Cost Analysis is performed for the entire site to further quantify ordnance contamination and confirm response strategies/contracting packages. Contracting options are then implemented to complete the response action. The process closely follows the CERCLA remedial response procedures.

OE RECORDS' SEARCH

Historical records are searched and obtained from approximately 100 Government (federal, state, local) repositories located throughout the United States and another 25 non-Government sources (national, state, local). Approximately 50 National Archives and Record Administration Record Groups are searched along with an additional 65 War Department File System files for each site. The search includes both classified and non-classified holdings and involves all types of OE documents. Typical documents include texts/manuals (TM's, FM's, supply catalogues/bulletins, TOE's), reports/studies (post histories, clearance reports, blotter reports), letters/memorandums, real estate documents, aerial photographs, and maps/ engineering drawings. Ordnance specialists oversee this phase for document usefulness and relevancy.

OE RECORDS EVALUATION

The OE records are analyzed by a team of ordnance specialists. Typical analyses include production/ manufacturing practice (process analysis, waste streams,

decontamination procedures), usage (range fans, target hazard zones, trajectory analyses, delivery weapon analyses), storage practice (includes re-conditioning and item maintenance), and disposal practice (burn pits, demolition ranges, burial sites).

SITE INSPECTION

The site is inspected by several ordnance specialists and other professionals as needed. Military ordnance expertise is again critical during this phase to correctly recognize and field evaluate ordnance presence. Field GPS equipment and magnetometers are used for surface / visual searches. Site interviews by the same qualified ordnance specialists (who have a full understanding of common ordnance practice at the time) with local authorities and owners can readily substantiate the truth regarding present day ordnance. Many sites reveal an immediate OE hazard which require an EOD response.

RESPONSE STRATEGY

The results of the above evaluations and analyses are published in the site ASR. Careful documentation of all sources is provided to allow independent verification of conclusions. Copies of all relevant historical documents are provided along with new OE evaluations and rationale. Particular emphasis is placed on segmenting the entire site into multiple homogenous "OE Project Areas". Homogenous areas are based on considerations of former and present land usage, OE contamination, current land ownership, political boundaries, and real estate standard practice. CADD drawings following tested layout procedures are produced which are then used throughout the remaining phases of the OE response. Overall recommendations include a risk assessment of each OE project area to insure high priority areas are addressed first. After completion of the ASR phase, a correctly completed ASR can continue to provide a road map or master plan for all subsequent OE response work.

U S Army Corps of Engineers

Rock Island District
Ordnance and Explosives Engineering

Time and Cost Benefits
of an
Archive Search Report

presented by

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U S Army Corps of Engineers, Rock Island District 3/14/96

Project Team
Teamed with COE / Army / DOD Explosives Safety

- CEHNC — Manage OE program as CX and Design Center
- CENCD — Provide liaison between CENCR and HQUSACE
- CExxx — Manage OE projects as Military design district
- **CENCR — Support CEHNC's and MilitaryDistrict's OE program**
- **USADACS* — Support CENCR with explosive safety (co-located with NCR)**
- MEDCOM — Support CENCR with Industrial Hygiene (co-located with NCR)

*United States Army Defense Ammunition Center and School / IOC/ AMC

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Outline

- Qualifications of ASR Team
- Basic Principles
- Evaluations and Report Content
- Results

U S Army Corps of Engineers, Rock Island District 3/14/96

Project Team
United States Army Defense Ammunition Center and School (USADACS)

Mission: Support Army Explosives Safety Program

- Ammunition Career Management
- Logistics Engineering
- **U.S. Army Tech Center for Explosives Safety (USATCES)**
- Demil Technology
- Logistics Review
- Army Ammunition School

U S Army Corps of Engineers, Rock Island District 3/14/96

OE Team Project Experience

- **PA** Preliminary Assessment
  - Inventory Project Reports
- **SI** Site Investigation
  - Archive Search Reports
  - Expanded Site Inspections
- **RI** Remedial Investigation (or Engineering Evaluation...)
  - UXO Field Support
- **FS** Feasibility Study (.../ Cost Analyses)
  - UXO Field Support
- **RD** Removal Design
  - Explosive Safety Submission (ESS)
- **RA** Removal Action
  - UXO Field Support
- **M&S** Management and Support
  - Project Information Retrieval System (PIRS)

U S Army Corps of Engineers, Rock Island District 3/14/96

Project Team
Teamed with COE / Army / DOD Explosives Safety

	CENCR	USADACS	TOTAL
Safety and Occ Health Spec (EOD'S)	7	-	7
QA Spec / Ammo Surveill.(QASAS)	11	10	21
Research Specialists	-	5	5
Chemical Engineers	2	-	2
Industrial Hygienist	1	-	1
Civil / Environmental Engrs	2	-	2
Engineering (CADD) Technicians	5	-	5
Engineering Aides	3	2	5
Elec Engr (diver / ord loc spec)	1	-	1
Total	**32**	**17**	**49**

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

ASR Purposes

- Provide site characterization
- Verify FUDS eligibility / boundaries
- Determine OE presence on subsite basis
  (Confirmed, Potential, Uncontaminated)
- Provide OE technical data
- Provide related HTRW and BD/DR considerations
- Provide recommended OE clean-up strategy

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Types of OE Analyses

- **Production / Manufacturing**
  - Process analyses
  - Building usage
  - Waste Streams
  - Decontamination procedures
- **Usage (Army, Navy, Air Force)**
  - Range fans
  - Maneuver areas / uses
  - Bomb target hazard zones
  - Trajectory analyses
  - Military unit / mission analyses
  - Delivery weapon analyses

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Definitions of OE Contamination

- **Confirmed** = live OE / energetics on site
  (end items, components, explosive soil)
- **Potential** = evidence of OE / nothing confirmed
- **Uncontaminated** = no OE evidence
  (includes expended small arms)

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Types of OE Analyses (con't)

- **Storage**
  - Storage practice
  - Re-conditioning practice
- **Disposal**
  - Burn pits
  - Demolition ranges
  - Burial pits

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Summary of Process

- **Records Search**
  - Government
  - Non-government
- **Site Safety Plan**
  - Initial hazards
  - Emergency contacts
- **Site Inspection**
  - Site dynamics / interviews
  - Visual inspection / identification / mapping
- **Final Report**
  - Records evaluations
  - Site inspection
  - OE analyses
  - Conclusions and recommendations

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Basis of OE Project Area Boundaries

(Goal: Develop homogenous OE areas)

- OE contamination
- Former usage
- Current land ownership
- Political boundaries
- Topographical features
- Real estate standard practice

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Final Report / Findings

Table of Contents

1. Introduction
2. Previous Investigations
3. Site Description
4. Historical Ordnance Usage
5. Site Eligibility
6. Visual Site Inspection
7. Site Ordnance Technical Data
8. Evaluation of Ordnance Hazards
9. Evaluation of Other Environmental Hazards

Appendices
Drawings

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Final Report / Reference Sources

Government

Federal

Department of Defense (Army, Navy, Air Force)
Department of Agriculture (NRCS, NFS)
National Archives
Department of Commerce (NTIS, NOAA)
Department of Energy
Department of Interior (FWS, NPS, BLM, USGS, BuRec)
Department of Transportation (FHWA, Coast Guard, FAA)
Smithsonian Institute
General Services Administration (Library of Congress)

State

State Agencies
National Guard

Local

County / community / townships / city

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Final Report / Conclusions and Recommendations

Table of Contents

Project Fact Sheet (Executive Summary)

1. Introduction
2. Conclusions
3. Recommendations

Risk Assessment Code Worksheets per site / subsite
Drawings

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Final Report / Reference Sources (con't)

Non-Government

National

Computer Searches (OCLC, DIALOG)
Military Associations

State

Universities
Regional Associations

Local

County / Community groups
City groups

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Final Report / Appendices

A Reference Sources
B References and Abstracts
C Glossary
D Texts / Manuals (historical document)
E Reports / Studies (hist doc)
F Letters / Memorandums (hist doc)
G Real Estate (hist and present doc)
H Newspapers / Journals (hist doc)
I Interviews (present doc)
J Photographs (present site)
K Photographs (hist doc)
L Maps / Drawings (reference and hist)
M Report Distribution (present ASR)

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Final Report / Drawings

- Site Plan
- Facility Layouts circa Year of Usage
- OE Evaluations
- OE Project Areas
- OE Project Area Enlargements
- Current Land Ownership's
- Site Inspection Photograph Locations
- Others

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Summary of Land Usage

- **Former Usage**
  Production, Usage, Storage, Disposal Practice
- **Present Owner**
  Listed by discrete OE project areas
- **Present Usage**
  Residential, Commercial, Agriculture, Recreation, Natural Res.
- **Size, acres**
  Boundaries based on best available information

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Ordnance Presence / Usage

Aircraft Using the Site

Aircraft	Type	Tactical Weapons	Practice Weapons
Grumman TBF Avenger	Torpedo Bomber	.30 cal mg .50 cal mg 5 in rockets 1 torpedo 2000 lb bombs	same same 2.25 in rockets practice torpedo 3,25,100 pract. bmb
Vought F4U Corsair	Fighter Bomber	.50 cal mg 20 mm cannon 5 in rockets 1000 lb bombs	same same 2.25 in rockets 3,25,100 lb pract bmb

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Ordnance Presence / Production

Production Areas

Line / Area Name	Bldg. No.	Production Operation	OE Contamination Potential
Line 1	111	Bomb wash pit	Soil TNT
Line 2	112	Amatol screening	Soil TNT
Area 2	–	Detonator loading (M1A1, M15, M17)	None
Assembly line	15	Constant temp mag.	XXX decontamination

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Ordnance Presence / Usage

Units Stationed at the Site during 1943-1945

Squadron	Type	Dates Stationed	Mission
VS-31	Patrol	Oct 42-Jan 43	Patrol sector of Atlantic...
(RN) 738	British Navy	Jul 43-Feb 45	Flight training...
VT-97	Torpedo Bomber	Mar 45-Apr 45	Instruction of carrier flight doctrine

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Ordnance Presence / Usage

Coast Artillery Battery

Name	Number of Guns	Caliber	Model	Years
Whiting	2	3 inch	M1903	1910-1942
House	2	6 inch	M1900	1910-1942
Tousard	3	12 inch	M1900	1910-1941
AMTB 922	2	90 mm	M1	1943-1945

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

Ordnance Presence / Evaluations

Ordnance Incidents (1965-1969)

Date	Ordnance	Intended Target	Actual Target	Eval. Basis
Oct 65	5 in proj	Flamenco Peninsula	Cayo de Luis Pena	Navy records
Jun 69	20 mm	Isla de Culebrita	Eastern Celebra	Marine records

U S Army Corps of Engineers, Rock Island District 3/14/96

U S Army Corps of Engineers

Archive Search Reports
Ordnance Presence / Evaluations

Basis of Potential OE at Select Sites

Area	Name	Basis of Potential
D	Celebra Island (eastern)	In standard safety zone
E	Cayo de Luis Pena	Incident report of being hit by stray rounds
J	Marine water minefield	Based on 1913 map and other documentation

Archive Search Reports
Ordnance Presence / Evaluations

Chemical Data of Ordnance Fillers

Explosive	Synonyms	Chemical Formula
Mercury fulminate	Mercuric cyanate	$Hg(CNO)_2$
Ammonium Nitrate	AN	NH_4NO_2
Tetryl	Trinitrophenyl-methyl-nitramine	$C_7H_5N_5O_8$

Archive Search Reports
Ordnance Presence / Evaluations

Additional Eligible Sites

Area	Former Usage	Current Owner	Current Usage	Acres	Basis
D	Short Rg Impact Area	DOI	Recreation	372	Target fans
E	Mine field	private name	Agriculture	438	Target fans and insp
F	Extended Rg Area	private names	Residential	299	Target fans, insp, eval.

Archive Search Reports
Ordnance Presence / Evaluations

Other Environmental Considerations

Location	Potential Hazard	Basis
Lower camp	Fuel tanks	Records / insp
SE of Luis Pena	Brass dump	Records / interviews / eval
Generator site	Transformers	Records / site usage

Archive Search Reports
Ordnance Presence / Evaluations

Summary of Site Specific Ordnance

Item	Model / type	Filler / weight	Fuze / type / model
**rocket, 3.5 in	M-30	WP,2.23 lb	M-404
	M-28A2	Comp B,1.88 lb	M-404
60 mm mortar	M69 trainer	inert	-
grenade	MK1A1 trainer	inert	-

**Item confirmed

Archive Search Reports
Summary of Conclusions

- Area x
- Former Usage
  - Production, usage, storage, disposal
- Present Usage
  - Res, comm, ag, rec, nat res
- Probable End Usage
  - Res, comm, ag, rec, nat res
- Size, acres
- Eligibility
  - Confirmed FUDS or IR, Potential FUDS or IR
- Ordnance Presence
  - Confirmed, Potential, Uncontaminated
- Risk Assessment Code

Archive Search Reports
Summary of Recommendations

- Area x
- PA Actions
  Amend or prepare INPR
- OE Actions
  NOFA, IRA, ESI, EECA
- HTW Actions
  Perform SI
- BD / DR Actions
  Evaluate the hazard

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
OE Clean-up Recommended Strategies

General OE Program Steps

	Most Projects	Some Projects	Few Projects
• Confirmed	EECA	IRA / EECA	NOFA
• Potential	ESI	EECA	NOFA
• Uncontaminated	NOFA	ESI	-

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Summary of Recommended Strategy Issues

ESI, EECA, IRA

- Rights of entry
  Landowner will assist with community relations
  Landowner has been very reluctant to participate
  Must coordinate work during non-growing season
- OE Detection Sweeps
  Heavy brush will influence sweeps
  Terrain is very slippery after heavy rains
  Soil is mixture of clay and stone rubble
  Endangered plant life on-site
- OE Disposal
  On-site destruction must consider nearby housing
  Site is heavily used by the public

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports
Summary of ASR Recommended Clean-up Strategies

(Based on 140 ASR's completed by CENCR through FY95)

Strategy	No. Sites
• IRA/ EECA	8
• EECA	29
• ESI	50
• NOFA	53

U S Army Corps of Engineers, Rock Island District 3/14/96

Archive Search Reports

ASR Results

(based on 140 FUDS sites by NCR through FY95)

	Acres	Percent
Uncontaminated	1,378,000	44
Potential	1,323,000	45
Confirmed	335,000	11

U S Army Corps of Engineers, Rock Island District 3/14/96

Rock Island District
Ordnance and Explosives Engineering

- Ordnance Engineering Experts
  100 years of EOD expertise
  300 years of Army, Navy, Air Force ammunition experience
- Partner with COE / Army / DOD OE Assets
  Huntsville Engineering and Support Center
  USADACS / IOC / AMC / DDESB
- Fully Trained and Equipped
  PA, SI, EE/CA, RD, RA
  Magnetometers, GPS, other field equipment
  CADD/ GIS/ Internet OE Anchor

U S Army Corps of Engineers, Rock Island District 3/14/96

A MAJOR STEP FORWARD IN THE CHEMICAL REMEDIATION PROGRAM

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ABSTRACT

The purpose of this paper is to provide you with a brief review of the Department of Defense's emergency response and remediation programs for found or recovered chemical agent-filled munitions. The first part of the paper provides a summary of how the response and remediation programs developed and operated. This is followed by a discussion of an initiative of the Program Manager for Chemical Demilitarization to develop a better approach to clean up chemical munition contamination. The last part of the paper provides information on where the initiative is heading in the near future.

The section discussing development of the programs is written so that you can also follow the changes in an organization's mission and its name. Current titles are then used throughout the remainder of the paper.

I would like to acknowledge the assistance of the Office of the Project Manager for Non-Stockpile Chemical Materiel and the Project Manager of the Small Burials Program Office of Teledyne Brown Engineering for their help with this paper.

PAST PROGRAM ACTIONS

Until recently, environmental remediation programs did not have the capability to clean up sites containing military chemical agents on a routine basis. What was available was an emergency response capability resident within the U.S. Army Material Command (AMC). The headquarters of the U.S. Army Armament, Munitions and Chemical Command (AMCCOM) retained command and control authority over field response elements. The field response elements, located at Aberdeen Proving Ground (APG), Maryland, were provided by the U.S. Army Technical Escort Unit (TEU); the Chemical Research, Development and Engineering Center provided agent monitoring and analysis support. The common remedial action was simply TEU responding to the scene of chemical agent or chemical munition contamination, assessing the problem, packaging the item(s) for transport and escorting the cargo to a chemical surety material (CSM) storage site. Soil that was grossly contaminated with a chemical agent was remediated, typically by a limited removal action, and not as a hazardous, toxic or radiological waste (HTRW) response action. Occasionally a chemical munition was encountered that was unsafe for transportation and storage. In such cases, the munition would be destroyed on site, by open detonation, after coordination with state and local authorities. The munition's contents were destroyed by thermal treatment as a result of the explosion.

A larger emergency response group, called the Service Response Force, could be fielded if the incident involved a large number of munitions, would last more than a few days or if significant risk was present. The structure and composition of the Service Response Force would be tailored to the nature of the emergency response problem. Augmentation forces could come from the U.S. Army Forces Command (explosive ordnance disposal specialists, logistical support), AMC (technical assistance, subject matter experts, trained chemical agent operation and support personnel), the Federal Emergency Management Agency, the Department of Health and Human Services, and other agencies as required.

In the late 1980's an ordnance and explosive waste (OEW) program was developing within the U.S. Army Corps of Engineers (USACE); this program would include chemical munitions. This program became the responsibility of the new Mandatory Center of Expertise (MCX) for OEW within the USACE, Huntsville Division (USAEDH), Huntsville, Alabama. The MCX quickly learned that CSM remediation sites presented them with unique and challenging problems. The MCX recognized the need to coordinate with AMC and AMCCOM to develop requirements and procedures for investigating CSM-OEW sites. A Memorandum of Understanding was drafted between the MCX, the newly-established Chemical and Biological Defense Command (AMCCOM elements) and the newly-established U.S. Army Chemical Materiel Destruction Agency (USACMDA) at APG, Maryland. The USAEDH was then in position to award OEW remediation contracts that contained provisions for cleanup of sites that could contain CSM. Significant policy issues involving remediation program activities, and incorporating regulations regarding procedures for handling CSM, begin to drive wheels of change in the Army's environmental program.

The challenge the Department of Defense (DoD) faced was that chemical agents and munitions were being discovered as more formerly used defense sites (FUDS) were developed into commercial properties or home sites. This challenge increased as the DoD began closing military bases under the Base Realignment and Closure Act. Also, the draft of the chemical arms control treaty, the Convention on the Prohibition of the Development, Production, Stockpiling, and Use of the Chemical Weapons and on Their Destruction, could apply to some recovered munitions. In 1991, the U.S. Congress directed the Secretary of Defense to organize a program to address the challenges of nonstockpile chemical materiel. The Secretary of the Army was designated the executive agent for DoD for chemical warfare-related materiel. The Secretary of the Army now has the responsibility to develop the programs and clean up non-stockpile sites. Refer to Figure 1 for examples of recovered chemical munitions.

The USACMDA became involved in OEW remediation programs by way of a newly-assigned mission-- destruction of non-stockpile chemical materiel. A new element of USACMDA was created to oversee this mission; its title is Project Manager for Non-Stockpile Chemical Materiel (PMNSCM). The PMNSCM was initially involved with storage, transportation and eventual disposal of chemical material recovered from OEW remediation sites. So we now have a joint CSM remediation alliance comprising contractor, USAEDH, and USACMDA elements to discover and recover (with the first two parties) and pack and ship (in coordination with USACMDA). The current name of USACMDA is the Program Manager for Chemical Demilitarization.

Section 176 of Public Law 102-484, the 1993 Defense Authorization Act, directed the U.S. Army to submit a report to Congress that identified the scope of the problem of non-stockpile chemical materiel (NSCM), the methods for its destruction, transportation alternatives, and cost and schedule estimates for its destruction. Five categories of NSCM were identified: buried chemical warfare materiel (CWM), recovered chemical weapons, former chemical weapon production facilities, binary chemical weapons, and miscellaneous CWM. Part of the overall response by the Army to the Public Law was the Non-stockpile Chemical Materiel Program *Survey and Analysis Report*, November 1993, published by USACMDA. Findings of this report indicate potential burials at 82 locations in 33 states, the U.S. Virgin Islands, and District of Columbia. Of the 82 locations, 48 are DoD installations and 34 are formerly used defense sites. Some of the 82 locations have multiple sites for a total of 215 potential burial sites. Figure 2 identifies the states with potential CWM burial sites.

By this time it had become obvious to all parties to the CSM remediation program that applying CSM rules to OEW remediation programs was impractical. The USAEDH moved ahead with its OEW remediation program and USACMDA moved ahead with its demilitarization program as Army Regulations were reviewed to incorporate national environmental policy and internal Army policy changes. Eventually, some rules regarding CSM changed when Army Regulation 50-6, *Chemical Surety*, took effect on February 1, 1995. Chemical agents, chemical munitions or containers of toxic chemical agents recovered from the ground or a disposal site, are now categorized as hazardous waste. The Resource Conservation and Recovery Act or the Comprehensive Environmental Response, Compensation and Liability Act now drive recovery actions.

THE NEW INITIATIVE

A major step forward in the program to resolve the problem of recovered CWM was the USACMDA release of a procurement action to acquire contractual services for disposal of recovered CWM--the new term for previously discarded CSM as defined in the new AR 50-6. This procurement contract for the "Small Burials Program" was awarded on June 1, 1995. The purpose of this contract is to provide a mobile and flexible field capability to demilitarize and dispose of recovered chemical munitions and agents. Teledyne Brown Engineering leads the contractor team as the prime contractor and will perform systems engineering services and integration and program management. Other team members (in alphabetical order) and their specialty areas are: EAI Corporation for sampling, analysis and laboratory training support; Earth Resources Corporation for design, development and operation of equipment analog to the objective systems of munition management devices; GEOMET Technologies, Inc. for surety laboratory capability; UXB International, Inc. for functions unique to handling and disposition of ordnance and demilitarization operations; VERSAR, Inc. for permitting, regulatory compliance and other services; and Laidlaw Environmental Services (Government Services), Inc. for hazardous waste storage and transportation services.

Team Teledyne has developed a flexible, but detailed, operational concept that can be applied in various ways to a hypothetical recovery location. A simple, sequential operational scenario is presented here for ease of discussion. Where RCWM is expected to be encountered, the USAEDH mobilizes an OEW remediation contractor to a site. The PMNSCM will direct Team Teledyne to mobilize and establish an interim holding facility (IHF) near the OEW site. Team Teledyne will set up and operate the IHF to receive and

store any RCWM encountered by the USAEDH contractor until Team Teledyne is directed to set up the Small Burials disposal facility. Team Teledyne will demilitarize and dispose of the RCWM after set up and check out of the disposal facility and a preoperational survey by the PMNSCM.

The equipment comprising the systems will be compact, decontaminable and transportable. The functional activities within the facility are similar to functions included in a stockpile chemical disposal facility. They are munition storage area (IHF); entry control; security; command and control; process; hazardous waste storage; air monitoring; laboratory; maintenance; supply; personal protective equipment issue, receipt, inspection and cleaning; medical; safety and work force support. Figure 3 depicts a conceptual site layout.

Chemical munitions will be moved from the IHF, through an airlock and into an environmental containment structure (ECS), which surrounds the unpacking area, the material handling area and the process trailers. The ECS is the outer envelope of engineering control for chemical agent liquid and vapor that may be released from primary or secondary agent control areas within the ECS. The ECS is made of a vapor-proof material supported by a metal structure, set up over a thick plastic ground covering, with a charcoal-filtered air handling system to maintain an internal negative pressure relative to the outside air pressure. Process trailers, set up within the ECS, will also have filtered air handling systems to maintain a negative pressure relative to the ECS while munitions are being processed. Activities that could result in release of chemical agent will be conducted within the ECS.

The chemical munitions, or other suspect containers, will be thoroughly assessed by the on-site disposal team to determine the type of agent fill, presence of explosive components and physical configuration of the munitions. Currently, we plan to use two items of equipment for evaluating each munition. The first is a portable isotopic neutron spectroscopy (PINS) device used to determine the presence of elements that would identify the presence of explosive and toxic material within the munition or container. Figure 4 shows a typical set up of the radiation and detector heads of the PINS. The second is x-ray equipment to evaluate the internal physical configuration of components. Results of this assessment will determine the process device to access the agent fill, type of decontaminant, orientation of the munition within the process device and other necessary safety measures.

Chemical munitions will be accessed and drained of agent by one of a family of munitions management devices (MMDs). These systems are currently under development or design and will be fielded only after successful testing. Nonexplosively configured munitions will be processed with the MMD-1; explosively configured munitions with the MMD-2; and large items, such as ton containers, bombs or drums with the MMD-3. Chemical agents drained from the munitions or containers will be analyzed for type of agent, chemically neutralized and analyzed to verify neutralization. The resulting liquid wastes will be transferred to shipping containers for off site disposal. Munitions will be opened or sectioned, decontaminated, inspected and certified clean, packed for shipment and disposed of off-site. Disposal of energetic materials will be determined depending on local and state regulations and amounts and types of material encountered.

When disposal of all recovered chemical warfare materiel is complete, the process equipment will be decontaminated, certified as "clean" and readied for shipment. Decontamination, preparation for shipment and other site closure activities will follow prescribed procedures. By starting decontamination activities at the location of highest expected contamination (for example, the MMD-1 pressure vessel) and working outward to the contamination control point, the system can be safely decontaminated and certified while maintaining engineering controls on the environmental containment structure surrounding the contaminated area. After all items within the ECS have been cleaned and verified free of agent, the air handling system will be shut down, the charcoal filters will be removed and packaged for disposal, and new filters installed. A final agent monitoring check can then be performed within the ECS. A similar closure process will then be conducted for the adjoining personnel decontamination trailer. Hazardous waste handling and storage areas will be cleaned and all waste material will be packaged and shipped off site for disposal. Individual operational or support trailers will be cleaned and readied for shipment to the next site; locally-leased support equipment will be returned to the appropriate vendors.

A new function recently given to the Small Burials Team is the test of the Rapid Response System (RRS) for the PMNSCM. The RRS is being developed to respond to incidents involving Chemical Agent Identification Sets (CAIS). These sets were training kits used by all military services from the 1930s to the 1960s that consisted of various glass bottles and vials containing numerous types of chemical agents and simulants. Commonly called "ID Sets," they are usually found in disposal pits or landfills on active military installations and formerly used defense sites. The RRS will be driven to a recovery site and operated by a small contractor team. The functions of the RRS will be breaching overpack materials, identification of the contents of the various bottles

and vials, destruction of military unique chemical agents and packaging of resultant waste materials for proper off-site disposal. The contents of the bottles and vials will be determined by evaluation of physical markings and analysis by Raman Infrared Spectrophotometer. Containers identified as containing industrial chemicals will be segregated, properly packaged and shipped to appropriate, permitted disposal sites. The RRS will consist of trailer-mounted glove boxes, air locks and process equipment and trailer-mounted support systems for convenient transportability and rapid setup. Figure 5 is a representation of the interior and exterior of the system.

WHERE WE ARE GOING

The Small Burials Program is moving along very well. The program consists of several tasks that will culminate in actual field demilitarization activities. The basic near-term tasks are:

- construct 100 single round containers
- design and construct a MMD-1
- design and construct a MMD-2
- design and construct a MMD-3
- set up and test the MMD-1 at Dugway Proving Ground, Utah
- test the RRS at Tooele Army Depot, Utah

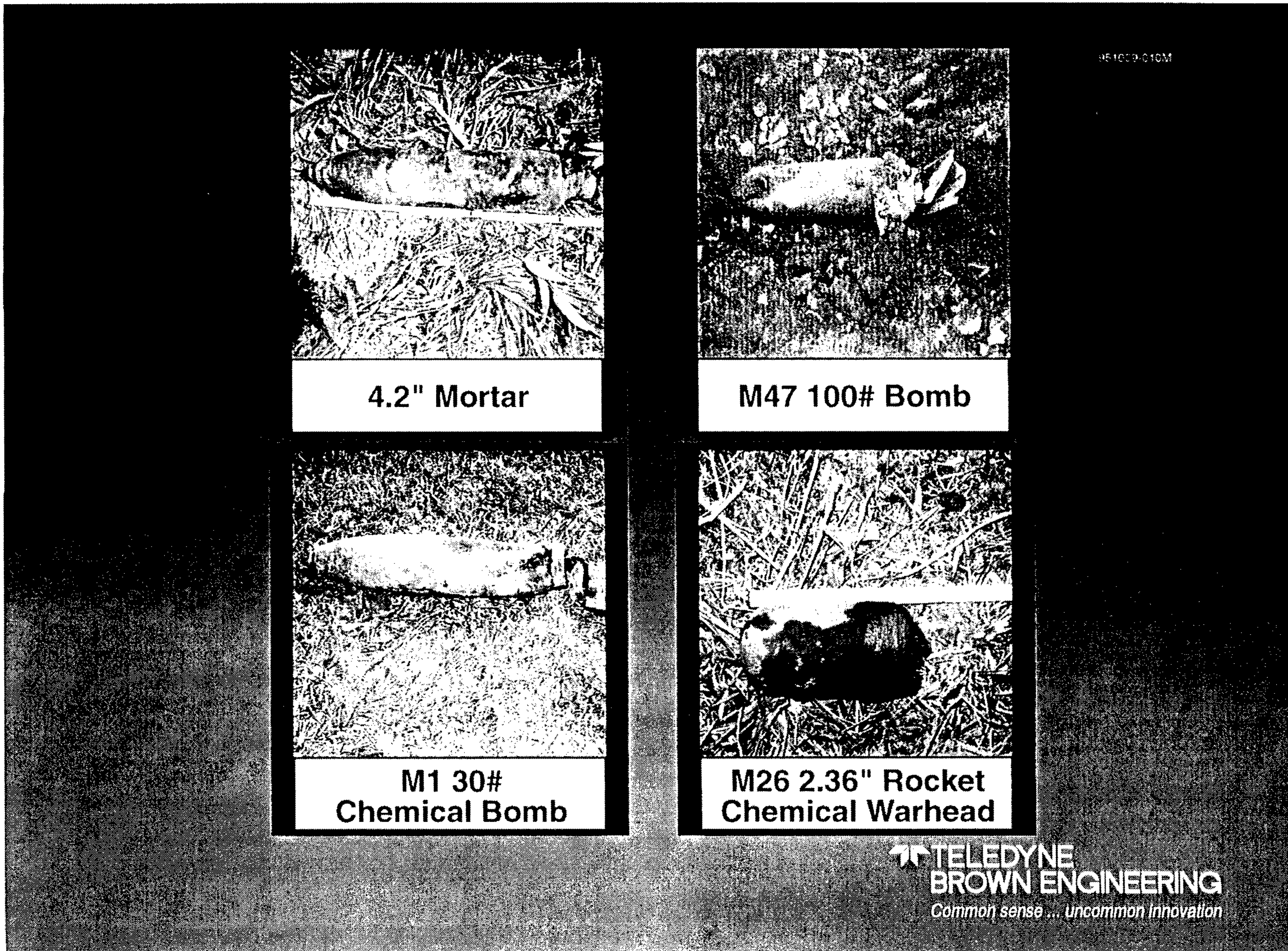
The current schedule of major tasks for the RRS is:

- 9 Feb - 3 Jul 96 -- qualification training
- 15 Jul 96 -- start setup in Tooele Army Depot, Utah
- 18 Jul 96 -- start operations with simulation hardware
- 6 Sep 96 -- start pre-operational survey summary
- 13 Nov 96 - 21 Jan 97 --CAIS operations

The current schedule of major tasks for the MMD-1 is:

- Aug 95 - 8 Aug 96 -- fabricate and assemble
- 14 Jun 96 - 28 Aug 97 -- test phase at Dugway Proving Ground, Utah
- Nov 96 - Jan 97 -- CWM operations
- Jan 97 - Jul 98 -- equipment modification, as required

The U.S. Army will soon be able to provide on-site disposal systems when chemical agent-filled munitions or containers are unexpectedly uncovered on active military installations or at formerly used defense sites. For those sites identified as probably having chemical contamination, the ability to plan for the controlled destruction of RCWM will enable the clean up of these sites in priority order. Whether the destruction of the RCWM is conducted on-site or at a nearby location, at least the process of disposing of this material has begun.



4.2" Mortar
M47 100# Bomb
M1 30#
Chemical Bomb
M26 2.36" Rocket
Chemical Warhead
TELEDYNE
BROWN ENGINEERING
Common sense ... uncommon innovation

Figure 1


951006-003M10
POTENTIAL CHEMICAL WARFARE MATERIEL
BURIAL LOCATIONS
No Sites
One Site
Multiple Locations/Sites
TELEDYNE
BROWN ENGINEERING
Common sense ... uncommon innovation

Figure 2

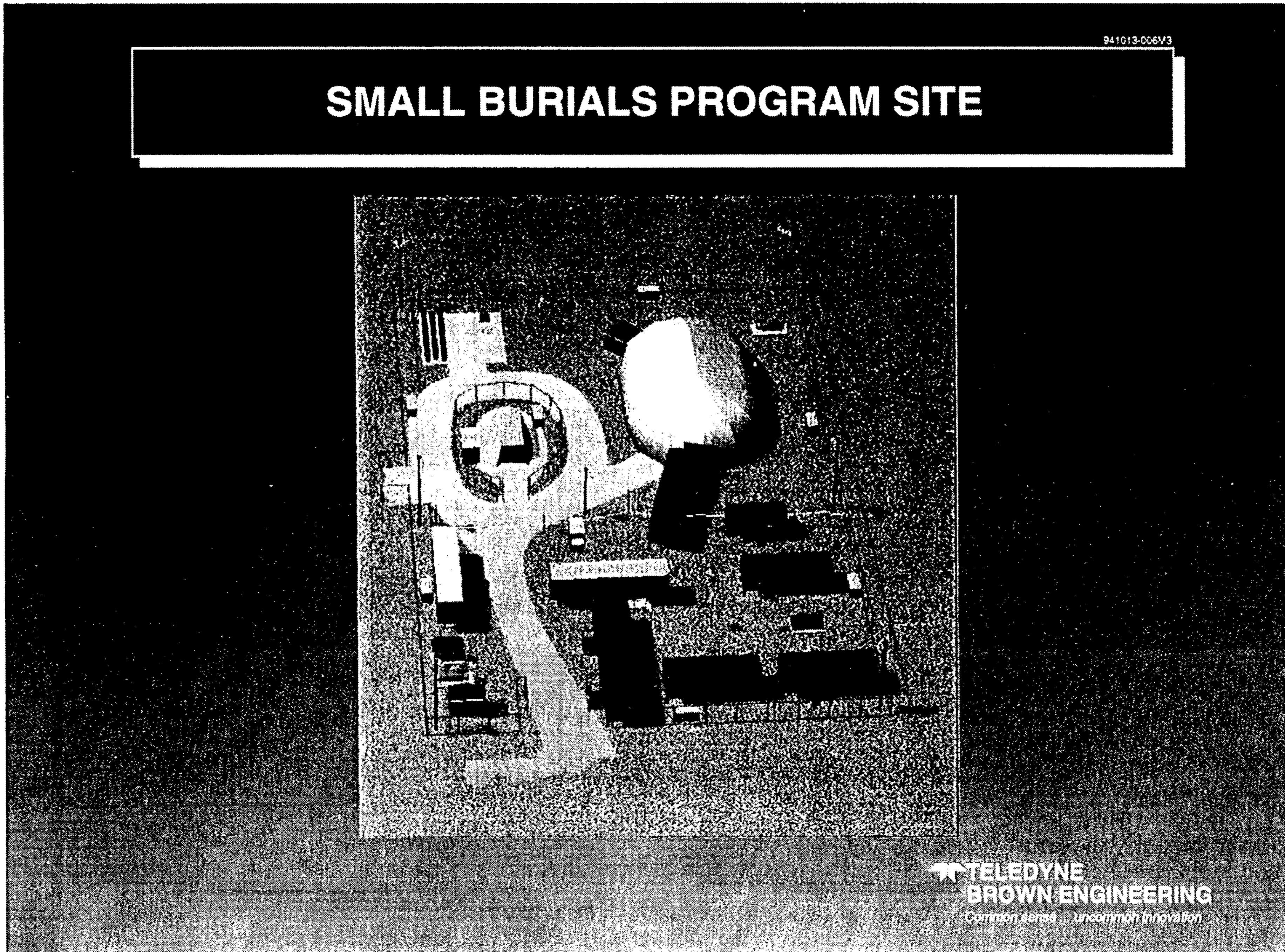

941013-006V3
SMALL BURIALS PROGRAM SITE
TELEDYNE
BROWN ENGINEERING
Common sense ... uncommon innovation

Figure 3

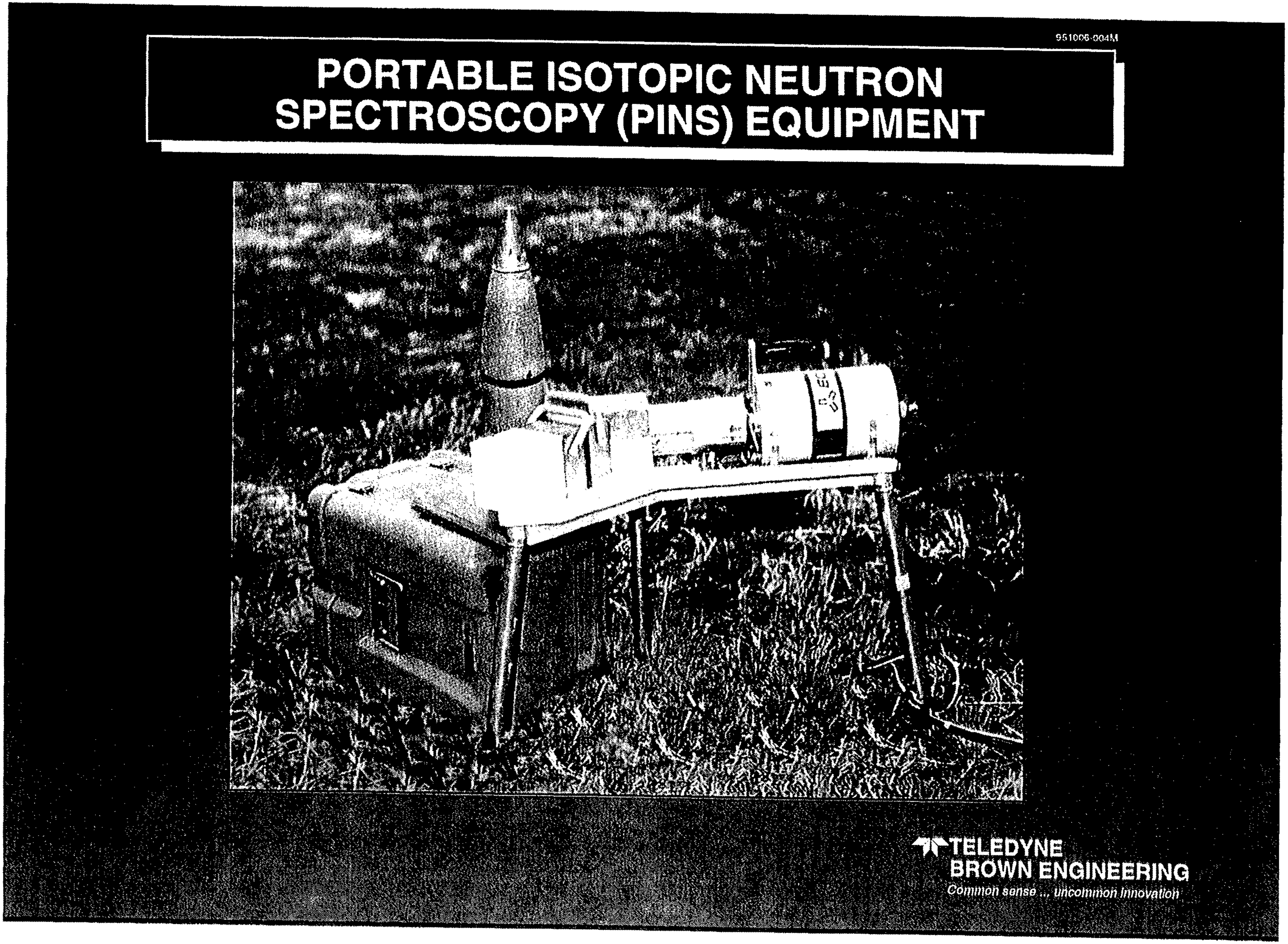

951006-004M
PORTABLE ISOTOPIC NEUTRON
SPECTROSCOPY (PINS) EQUIPMENT
TELEDYNE
BROWN ENGINEERING
Common sense ... uncommon innovation

Figure 4

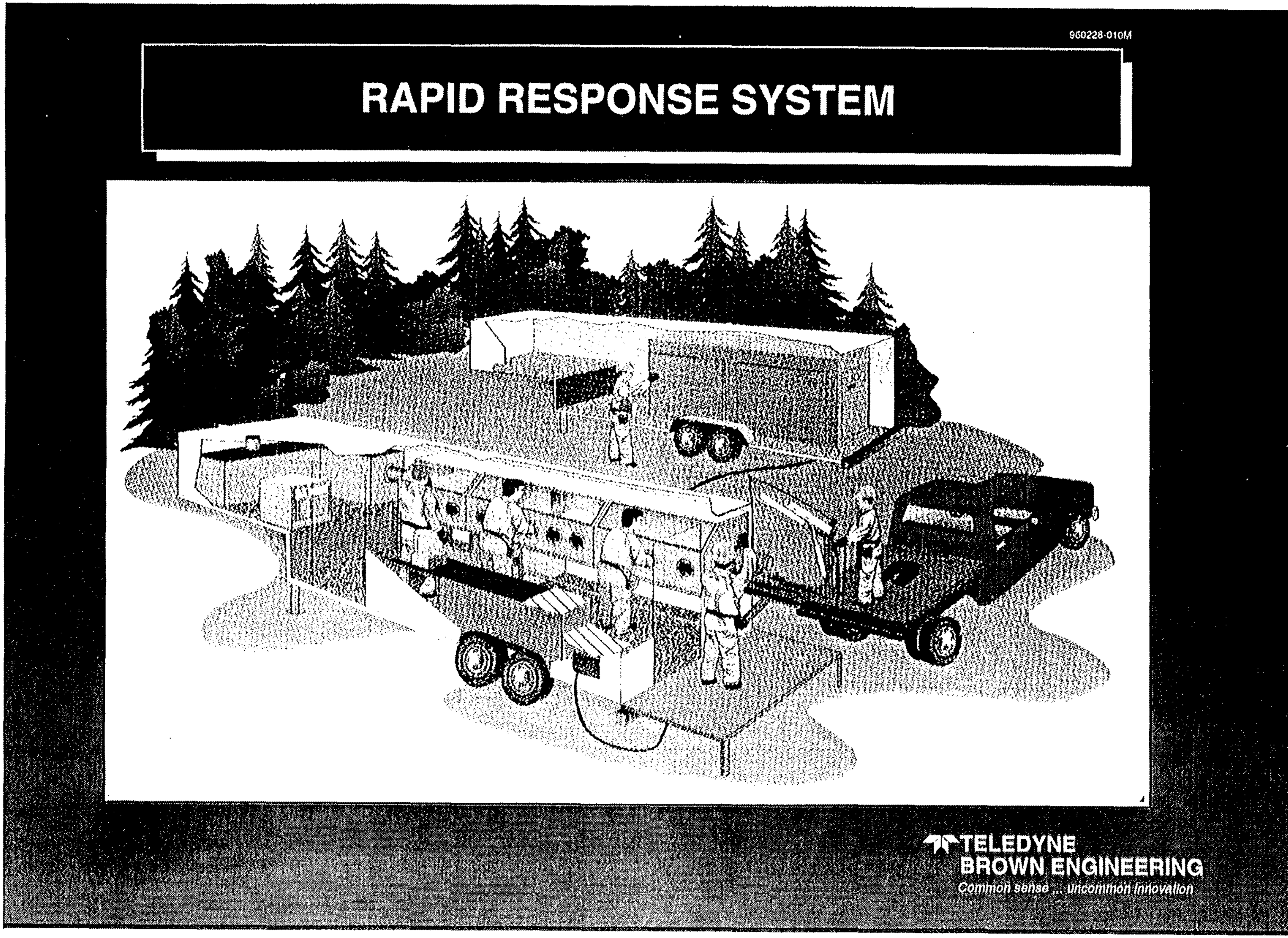

960228-010M
RAPID RESPONSE SYSTEM
TELEDYNE
BROWN ENGINEERING
Common sense ... uncommon innovation

Figure 5

APPLICABILITY OF COMMERCIAL PROCEDURES AND TECHNOLOGIES TO THE DESTRUCTION OF CHEMICAL WEAPONS MATERIEL

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ABSTRACT
The United States Army has identified both the technology and procedures successfully used in industry to sample, analyze, and recontainerize or treat hazardous chemicals as the basis for a number of systems that will be fielded to process chemical weapons and chemical warfare materiel as part of the Small Burials Program. The Small Burials Program is structured to remediate chemical weapons and chemical warfare materiel that have already been or will be recovered at over 200 suspected or known burial sites in the continental United States, Alaska, Hawaii and the Virgin Islands.

Teledyne Brown Engineering in Huntsville, Alabama assembled a team of specialty contractors to compete for the Small Burials Contract. Known as "Team Teledyne" a group of predominantly small businesses under the leadership of ***Teledyne*** was able to bring a cost effective approach to the Small Burials Program based on proven technology and procedures.

One of the members of Team Teledyne, **Earth Resources Corporation (ERC)**, has pioneered the development and operation of systems for processing compressed gases in deteriorated containers and is applying this same technology to a number of the systems being fielded in the Small Burials Program. **ERC's** approach to risk mitigation incorporates a combination of engineering control(s) as well as practices and procedures based on over fifteen years experience remediating hazardous chemicals on Superfund Sites, at Department of Defense and Energy facilities, on University campuses, and for major chemical manufacturers.

INTRODUCTION

In the past several years the specter of Chemical and Biological Weapons have drawn an increasing level of public interest. While not by any means do chemical and biological weapons represent a new threat, their lethality and potential effectiveness were eclipsed during the past fifty years by nuclear technology and advances in the precision of both long (intercontinental) and short (battle-field) range weapon delivery systems. But recent events such as the Japanese domestic terrorist attack using Sarin in a subway system and revelations about Iraq's chemical/biological warfare program remind us of the threat posed by these types of weapons. Public sensitivity and attention to chemical warfare issues, including destruction of weapons, will likely increase in the United States as the Army proceeds with plans to address the destruction of the U.S. Stockpile and if the Chemical Weapons Convention becomes a topic for debate during this year's political campaigns.

The point being made is the media and interest groups can be expected to raise the public awareness to both the threat and destruction of chemical weapons and chemical warfare materiels (CWM).

Industry in both this country and abroad routinely manufactures and uses chemicals that can present similar threats to life and the environment as CWM. Phosgene, cyanogen chloride, and cholopricrin all have industrial/agricultural applications. In addition to these toxic compounds it is not unusual for industrial wastes (in gas, liquid and solid states) to include combinations of toxics, pyrophorics, corrosives and oxidizers. Industrial disasters such as Bhopol with over 2,000 people killed still looms very fresh in the minds of many.

Industry has learned, often time based on catastrophic experience, what works to mitigate chemical risks and what does not. Clearly the Army is taking advantage of lessons learned by industry in the Small Burials Program. This program addresses a portion of the Non-Stockpile inventory of chemical weapons and CWM.

A number of systems, as well as procedures, have been developed by industry to safely and effectively process highly hazardous waste chemicals. These systems were developed to address both industrial and laboratory

materials and containers analogous to weapons materials that are within the scope of the Small Burials Program.

Earth Resources Corporation (ERC) is a pioneer in both the development and operation of such systems. As a member of ***Team Teledyne*, ERC** is bringing its expertise in the design, development, fabrication, testing and operation of such systems to the Army's Small Burials Program.

ERC's systems approach to remediating highly hazardous chemicals has driven the technology applied through a number of generations of refinement. Underlying the technology are what might be described as design tenets for process equipment:

1. Systems need to be highly mobile -- bring the solution to the problem and avoid further risks associated with transportation of hazardous and/or unstable materials;

2. Systems processing hazardous materials must have multiple levels of containment to mitigate against the possibility of an unintentional release;

3. Systems must be designed with enough modularity such that they can be reconfigured to adapt to unique circumstances that might be encountered during field operations;

4. Systems need to be remotely operated to minimize the risk to technicians;

5. Systems must have on-line emergency treatment capabilities in the event of an unintentional release within one or more of the levels of containment; and

6. Systems must be supportable in the field -- simplicity in design maximizing use of readily available commercial components.

ERC has learned that it is not possible to engineer humans out of operational considerations. In addition to these "design tenets" for systems **ERC** invests heavily in fielding trained, experienced, and well equipped crews that have a demonstrated history of working together as a team.

Not unlike the Army's dedication to accomplishing its assigned mission -- **ERC's** approach to project management is one of commitment to getting the job, the whole job, done right the first time. There is also a distinct economic advantage to doing a job just once.

The Army in carrying out its mission of destroying CWM must have the job done right the first time. There is NO margin for error or release. To accomplish this mission the Small Burials Program will develop and field a number of systems, each appropriate for a specific category of CWM or the type of container the munition is in.

The systems currently under development include:

Rapid Response System (RRS)
Munitions Management Device, Version 1 (MMD-1)
Munitions Management Device, Version 2 (MMD-2)
Munitions Management Device, Version 3 (MMD-3)
Munition Assessment and Processing System (MAPS)

RAPID RESPONSE SYSTEM (RRS)

The *Team Teledyne* involvement with the RRS exemplifies the "Team" approach to working with the Army on the Small Burials Program. The RRS is a system being developed and fabricated by the Ammunition Equipment Directorate at the Tooele Army Depot and SAIC specifically to destroy the contents of Chemical Agent Identification Sets (CAIS). CAIS were manufactured as field identification sets and contain industrial chemicals and chemical agents such as mustard, nitrogen mustard and lewisite.

The RRS hardware will be fielded in three transportable trailers: 1. a remote-operations trailer for treatment of CAIS, 2. a support utility trailer and 3. a supply trailer. The operations trailer will contain a filtered glovebox that will provide engineering controls and vapor containment for unpacking and segregation of these hazardous chemicals.

Those chemicals that are classified as industrial chemicals (such as phosgene) will be repackaged for shipment to a commercial hazardous waste facility. Those chemicals classified as CWM agents (such as mustard, nitrogen mustard and Lewisite) will be detoxified in a small chemical reactor, and the resulting waste products packaged for shipment to a commercial hazardous waste treatment facility.

Fabrication of the RRS is scheduled for completion this month (March 1996) with crew training beginning next month. Following training, the crew will initiate testing the RRS by destroying CAIS currently stored at Tooele Army Depot. After testing there will be an analysis of the test results. Any required modification to the RRS design will be addressed in this same time frame.

Team Teledyne is staffing this test with not only the requisite engineering to evaluate the RRS but with the operators and technicians with highly trained crews from **ERC** who have a broad range of experience in hazardous chemical operations under field conditions. A core team of these personnel have already begun familiarization training with the RRS and are enhancing operations, maintenance, and safety procedures based on proven experience in field conditions. **ERC**'s expertise in the execution of safe practices in the management of hazardous wastes and strict adherence to both Federal and State Regulations regarding the handling, storage, transportation, and disposal of such materials provide an essential element to the operation of the RRS.

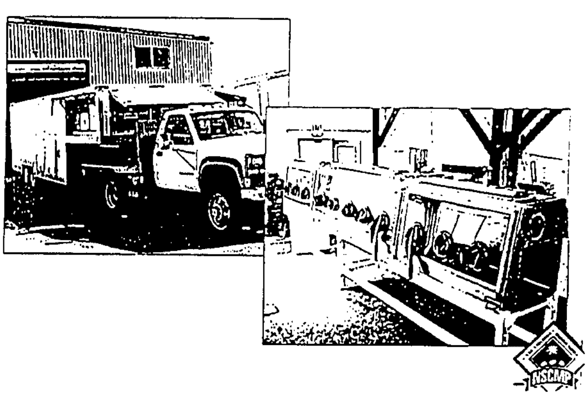

FIGURE 1 - RRS

MUNITIONS MANAGEMENT DEVICE, VERSION 1 (MMD-1)

The MMD-1 system was developed by SAIC and Tooele Army depot and is currently in the final stages of production and is scheduled for completion later this year with testing planned at Dugway Proving Ground (DPG). This system is designed to process non-explosively configured containers of CWM up the size of a World War II M78 (500-pound) chemical bomb.

The MMD-1 will allow the operator to remotely access the munition using tooling within a pressure vessel, sample the chemical to determine its identity and then cut a section off the munition body. Detoxification reagents will be mixed with the chemical, heat and cool the reaction, then process both the gas and liquid agents. The processing will be done under strict environmental and safety controls.

The spent detoxified chemicals will be packaged for shipment to a commercial hazardous waste disposal facility.

The prototype MMD-1 is being designed, acquired and assembled by the Program and Integration Support Contract (PAISC) Contractor. This effort is scheduled for completion in FY96. Plans are to test the prototype by treating nonexplosively-configured munitions currently stored at DPG. This test is currently scheduled to occur during FY96-FY97. Team Teledyne will operate the MMD-1 during this test.

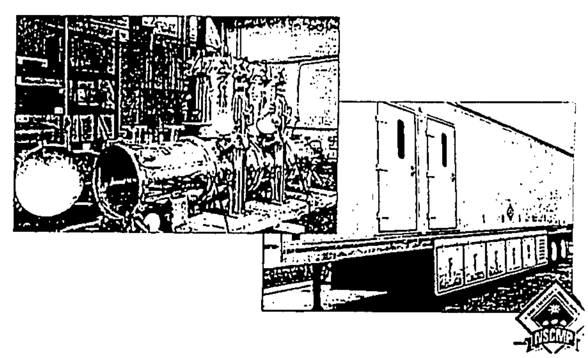

FIGURE 2 - MMD-1

The MMD-1 is very analogous to **ERC**'s Cylinder Recovery Vessel (**CRV**).

Often gas cylinders cannot be safely sampled through the valve mechanism due to the condition of the cylinder and its valve. Sampling cylinders through valves in poor condition results in the possibility of failure during sampling.

To address the problems associated with these cylinders, a system has been developed by **ERC** to safely control the hazards associated with these wastes. The system provides for sampling and recontainerization of the cylinder contents in a contained, inert environment. The **CRV** has proven to be an effective mechanism to overcome the myriad of problems posed by these wastes.

Figure 3 illustrates the principal components of the system.

The vessel and system were designed to accommodate the high pressures and wide variety of gases and liquids available in common commercial gas cylinders. The **CRV** is a steel, ASME-rated pressure vessel. Appurtenances to the vessel include a cylinder clamping mechanism, a hydraulic drilling system, high pressure nitrogen gun, and vacuum purge system.

Interior pressures and temperatures are monitored by remote sensing units. The **CRV** is located inside a sealed tractor trailer van. All of its systems are hydraulically or pneumatically controlled.

The entire system is operated from a remote panel located adjacent to the process area. From the command control panel, operations are monitored (via video cameras) and controlled while all personnel are removed from the process area.

A secondary containment chamber houses the **CRV** and its recontainerization systems. This reinforced steel chamber is sealed to contain any release from the primary system. All of the equipment in the chamber is suitable for operation in Class I, Division II explosive environments.

A major reason for using the **CRV** is to obtain samples for identification of cylinder contents. The **CRV** incorporates sampling ports for gas withdrawal. A sample is obtained and transferred directly to an on-site analytical unit, the Mobile Laboratory, for analysis. The analysis is completed, and the gas can then be recontainerized into a DOT-rated vessel for off-site disposal, or can be treated on site.

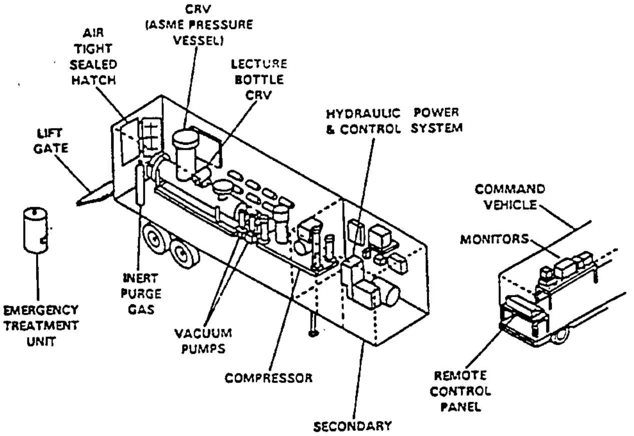

FIGURE 3 - CRV

Most compressed materials can be handled in the gaseous phase. Liquefied gases may be volatilized and recontainerized in the **CRV** through its vacuum system. The system can also accommodate liquid withdrawal.

MUNITIONS MANAGEMENT DEVICE, VERSION 2 (MMD-2)

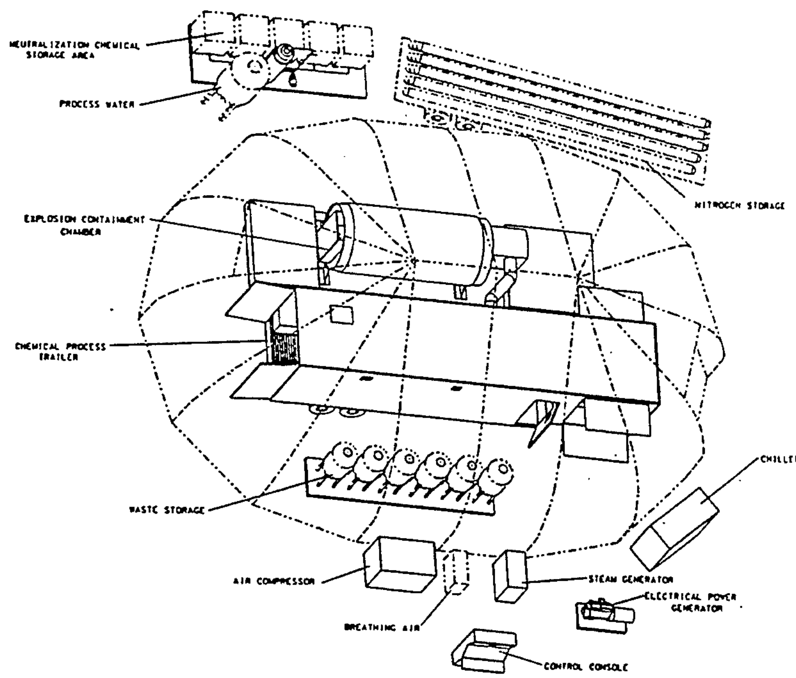

FIGURE 4 - CONCEPT FOR AN MMD-2 SYSTEM

The disposal of explosively-configured CWM is more complex than disposal of other CWM.

The equipment to destroy explosively-configured CWM is designated as the MMD-2. The MMD-2 will be completely developed by ***Team Teledyne*** from concept through fielding. It will be designed to handle a variety of munitions up through the 8-inch chemical projectile, and to fully contain any potential blast and pressure release resulting from operations.

The site for MMD-2 testing has not yet been determined. Explosively-configured recovered CWM will be used as test material in early FY98. The environmental permit application process to support the test will begin FY96.

ERC technology for accessing the contents of a container as well as mobile chemical processing are being applied to development of the MMD-2.

The MMD-2 Drill and Extraction Mechanism is a derivative of the ERC field-proven method of neutralizing compressed gases. Both systems are designed to access cylinders or weapons containing toxic and/or reactive gases. The three main differences are: a) The munitions processed by the MMD-2 are unlikely to contain materials under pressure (some effervescence may be encountered with mustard.)
b) The physical configurations of the munitions shells vary widely, ranging from spheres 2½ inches in diameter to tapered cylinders over 8 inches in diameter, several feet long. The shell thicknesses range from 1/32 to 3/4 inch.
c) Since some may be weapons recovered from burial sites, they may be corroded and/or in poor physical condition.

Figure 5 shows the MMD-2 Drill and Extraction assembly attached to the Auxiliary Pressure Vessel (APV), the equivalent of ERC's Cylinder Recovery Vessel (CRV) used in compressed gas management. The APV is mounted on a carriage within an Explosive Containment Chamber (ECC). This double level of containment ensures that no chemical or agent will escape to the atmosphere.

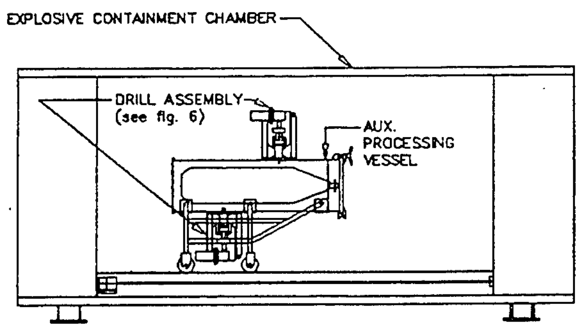

FIGURE 5 - MMD-2 DRILL & EXTRACTION ASSEMBLY ATTACHED TO APV WITHIN EXPLOSIVE CONTAINMENT CHAMBER

Sealing of the munition around the drill area is provided by a two-tier system consisting of an adapter fabricated for each type of munition and bonded to the shell, and a seal cup around the access point the APV. Similar to the CRV, the munition is drilled at two diametrically opposite locations. Extraction of the chemicals is accomplished by injecting a fluid through the top drill point and removing the mixture through the bottom drill point.

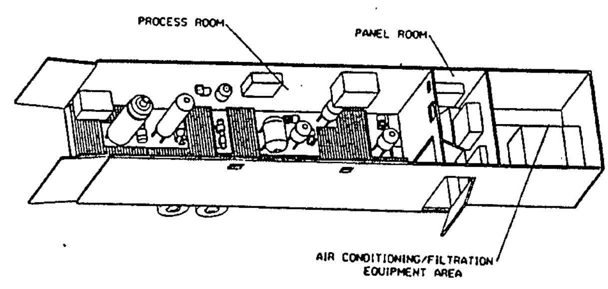

FIGURE 6 - MMD-2 AGENT NEUTRALIZATION SUBSYSTEM

Once CWM is extracted from a munition or container it is transferred to the Agent Neutralization Subsystem. The Agent Neutralization Subsystem is analogous ERC's Hazardous Gas Abatement System (HazGAS™).

The HazGAS™ system is a complete treatment system that is enclosed in a mobile trailer. The system is housed in a reinforced trailer unit that includes an "air tight" secondary containment chamber, video monitoring and remotely operated controls.

A standard HazGAS™ Treatment unit is illustrated in Figure 7.

The unit is comprised of *six (6) separate treatment options* that may be used singularly or in any combination to maximize both the efficiency and the effectiveness of the treatment operation. These include granular activated carbon and molecular sieve adsorbent units, thermal oxidation units, and three types of liquid reactors.

The liquid reactors are used to treat reactive gases. As the gas flows through the appropriate solution, it is reacted out eliminating it from the flow. The system houses a caustic, an acid and an oxidizing unit.

The HazGAS™ unit is equipped with a unit designed to thermally destroy many of the flammable gases. Exhaust from the thermal oxidation system is returned to additional systems for removal of oxidation products.

The system also contains adsorption systems. The material is transferred from a gas into a solid, which in turn is disposed of as a solid waste.

The mobile **HazGAS™** treatment unit is designed to accommodate treatment of *virtually all compressed gases*. The "closed-loop" design, a subject of pending patent application, assures that any exhaust meets applicable regulatory criteria.

There are several ways that material is introduced into the treatment system for processing. One is to pipe the released contents of the cylinder into the **CRV** directly to the **HazGAS™** Unit. The two (2) systems are designed to interact and complement each other. In addition, cylinders in good condition and with operable valves are directly manifolded into the treatment system.

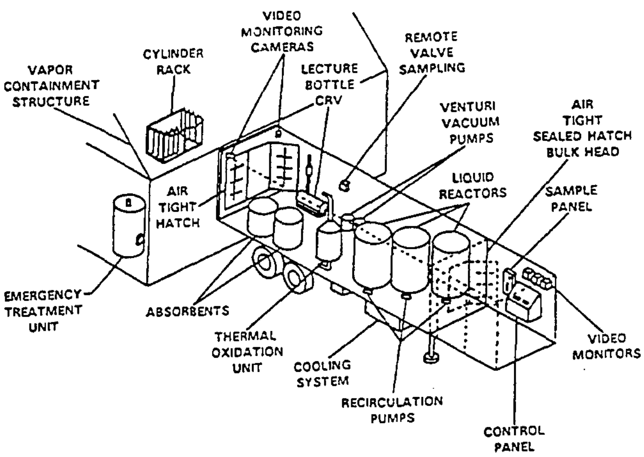

FIGURE 7 - HAZARDOUS GAS ABATEMENT SYSTEM (HazGAS™)

MUNITIONS MANAGEMENT DEVICE, VERSION 3 (MMD-3)

Primarily designed to process the contents of non-explosively configured munitions larger than a 500-pound bomb and bulk containers of CWM the Army will field the MMD-3. Incorporating a drill mechanism similar to the MMD-2, the MMD-3 will extract the CWM contents from munitions and transfer them to a Agent Neutralization Subsystem.

The MMD-3 will also have the capability to recontainerize compounds such as phosgene into a Department of Transportation approved container for shipment to a hazardous waste disposal facility.

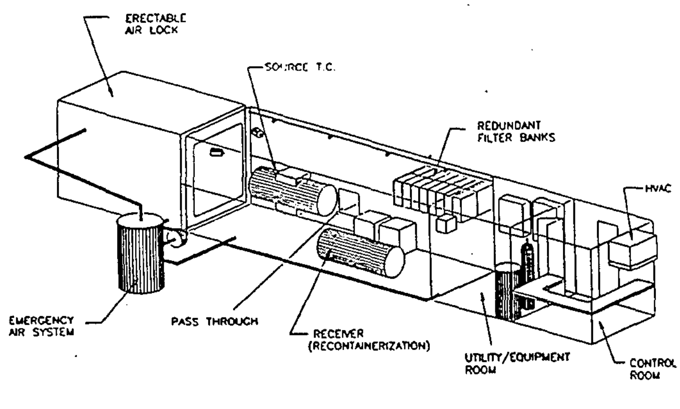

FIGURE 8 - CONCEPT FOR MMD-3

The MMD-3 design is similar to **ERC's** Large Cylinder Transfer Unit (LCTU).

The LCTU was designed to address the problems associated with sampling and recontainerizing or treating the contents of large containers, such as on-ton cylinders. The LCTU provides multiple levels of containment, remote operations and an emergency treatment capability.

ERC will design and fabricate the MMD-3 based on the field proven technology of it's LCTU. The MMD-3 design phase is currently scheduled to occur in FY96, with fabrication scheduled to begin late in FY96. The projected MMD-3 test will be conducted on a large, non-explosively-configured bomb during FY97.

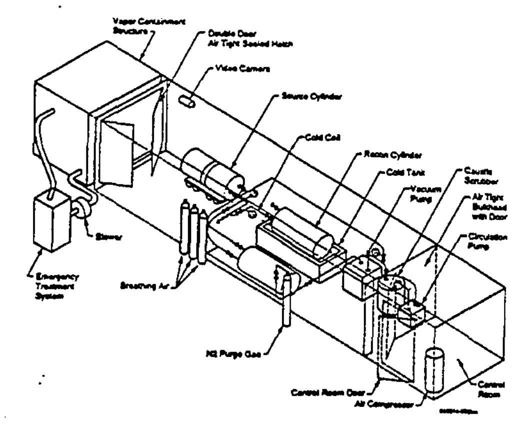

FIGURE 9 - LARGE CYLINDER TRANSFER UNIT (LCTU)

MUNITION ASSESSMENT AND PROCESSING SYSTEM (MAPS)

The MAPS is the only system being developed by Team Teledyne which is not mobile. This system is being designed for permanent operations at the Edgewood Area, Aberdeen Proving Ground.

MAPS function will be similar to that of an MMD-2 in that it will be accessing the contents of explosively configured munitions, however, like the MMD-3, it will have a capability to recontainerize the contents of the object accessed.

The Munition Assessment and Processing System (MAPS) is being designed to operate in a fixed facility environment with a capability of accessing chemical munitions and decanting the contents into Department of Transportation (DoT) approved containers. The MAPS will be capable of processing 75mm, 105mm, and 155mm and Livens projectiles as well as 4" Stokes and 4.2" mortar rounds.

Munitions will be delivered to the MAPS facility in overpacks in much the same way rounds will be transferred to a MMD system on a Small Burials Site. The overpacked munition is transferred into a Process Box where it is unpacked. Once the round is unpacked a variety of techniques including both x-ray and portable isotropic neutron spectroscopy (PINS) may be used to verify or identify the contents of the munition.

The round is then moved into the adjoining Glove Box where the drill and extraction sub-system is housed. The Glove Box is then disconnected from the Process Box and with the munition in place in the Glove Box the entire assembly is moved into an explosion containment chamber (ECC).

The actual accessing operation will be performed by a remotely operated drill and extraction sub-system similar to that which will be used in the MMD-2. After the drilling operation is complete the Glove Box is moved out of the ECC and reconnected to the Process Box where the munition is repositioned for decanting of contents into a DoT container.

The Drill and Transfer Subsystem is an application of ERC's accessing technology and the Glove Box where actual munition accessing operations will be conducted are an adaptation of a conventional laboratory glove box with significantly enhance structural integrity and fixtures for manipulating chemical weapons.

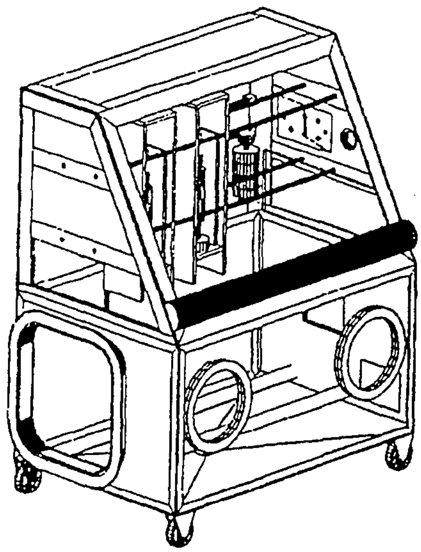

FIGURE 10 - CONCEPT DESIGN FOR MAPS GLOVE BOX WITH REMOTELY OPERATED DRILL AND EXTRACTION SUB-SYSTEM

It is evident the Army has developed a well conceived program for tackling the Non-Stockpiled Chemical Materials. This program maximizes the use of commercially readily available technology that has been proven both safe and effective in processing highly hazardous chemicals. Risk mitigation is paramount -- the Small Burials Program can not be a learning experience.

The Small Burials Program is fielding Mobile Systems, Systems that are specifically designed to mitigate the risks of the munitions and materials featuring Multi-levels of containment, remote operations, emergency treatment, and readily supportable in the field. In addition to the engineering require to design, develop, and fabricate these systems Team Teledyne also brings the Small Burials Program the expertise in conducting hazardous waste and chemical remediation operations with highly trained and experienced operational crews.

REMEDIATION OF CHEMICAL WARFARE MATERIEL

A CASE STUDY:
DEFENSE DISTRIBUTION DEPOT OGDEN, UTAH
OPERABLE UNIT 3

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This technical paper presents a discussion of the Defense Distribution Depot Ogden, Utah (DDOU) Operable Unit 3 (OU 3) remediation. Successful remediation of this chemical warfare materiel (CWM) site under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) has provided a valuable learning experience that will benefit future CWM remediation projects.

BACKGROUND

The DDOU facility, located in Ogden, Utah, is a key installation in the Department of Defense supply system. Since 1941, the Defense Logistics Agency has used the facility to store, maintain, and issue non-ordnance items to military installations and Federal and civilian agencies. In the 1980s, DDOU was proposed for placement on the National Priorities List and a site characterization began. OU 3 was subsequently identified and investigated under a Federal Facility Agreement between DDOU, the U.S. Environmental Protection Agency, and the Utah Department of Environmental Quality.

OU 3 consists of several distinct burial areas in which chemical agent identification sets (CAIS) and other miscellaneous items were disposed. CAIS were manufactured and distributed by the U.S. Army from the 1930s to the 1960s for military training in the detection and identification of various chemical agents. CAIS typically contain a number of small glass vials or bottles with chemical agent solutions, agents absorbed in activated charcoal, or undiluted liquid agents. The glass bottles were typically packaged in metal containers within a larger wooden box or steel cylinder with a flanged end cover (commonly referred to as a "pig").

Investigations suggest that K941, K951/952, and K955 CAIS, or the components of those identifications sets, were disposed at OU 3. Based on the known contents of those sets, the following CWM compounds or their degradation products were identified as contaminants of concern during the OU 3 investigation and remediation:

Lewisite	Mustard
Thiodiglycol	Adamsite
Chloroacetophenone	Chloropicrin
Phosgene	Triphosgene

It is noteworthy that other chemical compounds, not associated with CWM, were also detected during remedial investigations at OU 3. As the focus of this paper is remediation of CWM and the unique considerations

associated with it, a discussion of these additional contaminants will not be presented.

OPERABLE UNIT 3 AND THE CERCLA PROCESS

Investigation and remediation of OU 3 was undertaken by DDOU with assistance from the U.S. Army Corps of Engineers, Huntsville Engineering Center (CEHNC) and their consultants, the U.S. Army Technical Escort Unit (TEU), and the Project Manager for Nonstockpile Chemical Materiel (the Department of Defense's executive agent for the destruction of nonstockpile chemical materiel). Reviewing regulatory authorities included the Utah Department of Environmental Quality and the U.S. Environmental Protection Agency. These activities were generally conducted in accordance with the distinct phases of work required under the CERCLA process, including:

- Preliminary Assessment/Site Investigation (PA/SI)
- Remedial Investigation/Feasibility Study (RI/FS)
- Record of Decision (ROD)
- Remedial Design
- Remedial Action

PA/SI activities typically include those actions necessary to assess the background of a site and any potential environmental impacts. PA/SI activities were conducted on a Depot-wide basis and were documented in a variety of reports and technical memoranda.

In November of 1989, DDOU entered into a Federal Facility Agreement with the U.S. Environmental Protection Agency and the Utah Department of Environmental Quality. The purpose of the agreement was to establish a procedural framework and schedule for developing, implementing, and monitoring appropriate response actions at DDOU. Four operable units, including OU 3, were identified as a result of this agreement. Activities conducted after the execution of the Federal Facility Agreement were considered part of the RI/FS phase of the OU 3 project.

Investigations at OU 3 were conducted between 1981 and 1991. Activities included reviewing aerial photographs, installing monitoring wells, collecting groundwater samples, conducting geophysical surveys, excavating test pits, and collecting soil samples. Following is a brief chronology of those events:

- 1981 through 1991 - During this time period, shallow monitoring wells were installed by various contractors in the immediate vicinity of OU 3 and groundwater samples were collected. Analytical data indicated that no CWM was present in the shallow groundwater underlying OU 3.

- 1985 - A DDOU contractor conducted a review of available aerial photographs to delineate waste disposal areas. A magnetic survey was conducted in an attempt to confirm the presence of those disposal areas.

- May to June 1988 - TEU excavated 24 test pits to investigate those areas suspected of being impacted by disposal activities. The locations of the test pits were based on the findings of the aerial photograph review and the geophysical survey. During investigation of one of the burial areas, 110 small glass containers of CWM were recovered and transported to Tooele Army Depot for storage.

- November 1989 - An additional geophysical survey was conducted by the U.S. Army Waterways Experiment Station to further delineate potential disposal areas within OU 3.

- November 1990 to January 1991 - Montgomery Watson and TEU excavated an additional 36 test pits and collected soil samples. No CWM was detected in the soil samples collected during this investigation.

On behalf of DDOU and CEHNC, Montgomery Watson (formerly James M. Montgomery, Consulting Engineers, Inc.) prepared the *Draft Final Remedial Investigation/ Feasibility Study Report for Operable Unit 3* (JMM, 1991). This document presented a complete history of the investigations conducted to date, a summary of site-specific characteristics including the nature and extent of contamination, a baseline risk assessment, and an evaluation of potential remedial alternatives. Those alternatives included 1) no action, 2) institutional controls, 3) on-site treatment and off-site disposal, and 4) off-site treatment and disposal. If implemented, alternatives 1 and 2 would involve no active remediation of the site. Alternative 3 required excavation of soil and debris, sieving to physically separate the soil from the debris, and off-site disposal of the debris. Soil which met remediation criteria would be returned to the excavation and used as backfill. Alternative 4 also required excavation of soil and debris but differed from Alternative 3 in that all excavated material would be disposed off-site. Based on a comparative evaluation of the alternatives, the RI/FS Report concluded that a number of the alternatives may be appropriate given the contaminants and material observed in the burial areas within OU 3.

In 1992, Montgomery Watson assisted DDOU and CEHNC in preparation of the *Final Record of Decision and Responsiveness Summary for Operable Unit 3* (ROD; JMM, 1992). This was the primary decision document for

selection of a remedial alternative and its preparation required public input and incorporation of relevant comments. The ROD set forth the minimum requirements for remediation of OU 3 by establishing alternatives 3 and 4 (see above) as the selected alternatives (depending on the burial area being remediated).

Following execution of the ROD, Montgomery Watson prepared a series of remedial design documents which set forth detailed procedural and administrative requirements for remediating OU 3. The documents were prepared in accordance with U.S. Army Corps of Engineers (USACE) Guide Specifications and were intended to be used by USACE as the contractual vehicle to retain a civilian contractor to implement the remediation. During preparation of these documents, the conservative decision was made to excavate all material within the OU 3 burial areas for treatment and off-site disposal (i.e., alternative 4 identified above). This decision was reached based on the potential for encountering CAIS components in any of the OU 3 burial areas, despite the fact that significant remedial investigations indicated that they were only present in a portion of the burial areas. Final design documentation was published in July 1993.

Remediation of OU 3 began under civilian contract in October 1993 with the excavation of a burial area not associated with CWM (this was the only burial area in which remedial investigations conclusively indicated that CWM was not present). Prior to remediation of the areas where CWM may have been encountered, DDOU and CEHNC concluded that the remainder of the remediation would be conducted by TEU. This was an appropriate decision given the requirement that any civilian contractor must cease site operations in the event CWM is encountered. TEU would have been required to respond and recover the CWM prior to the civilian contractor resuming operations.

Prior to TEU beginning remediation activities, the requirement to prepare a "Safety Submission" was identified by the Department of the Army. The OU 3 Safety Submission provided a detailed analysis of the hazards associated with CWM and specified proper field and safety procedures to be followed during remediation of the site, including recovery, temporary storage, and transportation of CWM. Montgomery Watson finalized and published the OU 3 Safety Submission in July 1994.

The remainder of the OU 3 remediation was conducted by TEU during the Fall of 1994 and Spring/Summer of 1995. Montgomery Watson assisted TEU by providing construction oversight services. Soil and debris was excavated from the remaining burial areas and hand sifted prior to transportation off site. With the exception noted below, recovered CWM (15 containers of mustard, 1 container of lewisite, and 1 unlabeled container) was transported by TEU to Tooele Army Depot for storage and ultimate destruction. Two containers of lewisite and two containers of chloropicrin were transported to the Edgewood Research, Development, and Engineering Center for research purposes. All remaining soil and debris (605 cubic yards) was transported under USACE contract for disposal at a hazardous waste landfill in the State of Utah.

Following completion of the remediation, Montgomery Watson prepared the *Operable Unit 3 Remedial Action Report* (Montgomery Watson, 1995). This document presented a summary of the OU 3 remedial action, including a chronology of events and significant findings, and a summary of performance standards and construction quality control. All cleanup performance goals established in the OU 3 ROD (JMM, 1992) were met.

KEY ISSUES AND CONSIDERATIONS FOR CONDUCTING CWM REMEDIATIONS

The OU 3 remediation illustrates the requirements for investigating and remediating a site under CERCLA. The presence of CWM also dictated that a number of unique issues be addressed as the project evolved. These considerations will be common to any CWM investigation or remediation and should be addressed as early in a project as possible. Following is a discussion of these critical issues.

Coordination and Schedule

Conducting a CERCLA site investigation/remediation typically requires the involvement of multiple parties, including facility representatives and the regulatory and public communities. The presence of CWM also requires that a number of Department of Army agencies provide input and review and approve relevant documentation prior to implementation of any on-site activities. In the case of OU 3, the following organizations were involved in preparing and/or reviewing and approving site documentation, and implementing site activities:

- DDOU Environmental Protection Office
- DDOU Public Affairs Office
- DDOU Safety
- DDOU Security Police
- U.S. Army Corps of Engineers, Huntsville Engineering Center
- U.S. Army Technical Escort Unit
- Defense Logistics Agency
- Project Manager for Nonstockpile Chemical Materiel

- Edgewood Research, Development, and Engineering Center
- Department of Human Health Services
- Department of Defense Explosives Safety Board
- U.S. Environmental Protection Agency
- Utah Department of Environmental Quality
- Montgomery Watson and its subcontractors.

Due to the large number of organizations involved in the OU 3 project, it was critical that a strong sense of partnership be maintained among all the parties. A solution-oriented approach to remediating the site was fostered by conducting numerous brain-storming and on-board review meetings.

Because of the large number of organizations involved, scheduling was also a key consideration in the OU 3 remediation. CERCLA statutes and the Federal Facility Agreement executed between DDOU, the U.S. Environmental Protection Agency, and the Utah Department of Environmental Quality required that a rigorous schedule be established and maintained during the design and remediation phases of the project. DDOU successfully maintained the OU 3 project schedule by aggressively coordinating with all organizations and resolving critical issues in a timely manner.

Future CWM remediations should incorporate a "partnering" element to enhance teamwork, cooperation, and communication and facilitate definition of a structure for issue resolution. Facility personnel or their designated representative(s) should aggressively resolve key issues.

Documentation Requirements

This paper has summarized the typical documentation requirements for a CERCLA investigation/remediation. The Safety Submission is a Department of Army requirement for those sites involving CWM. This document ensures that proper field and safety protocols will be implemented in the investigation or remediation of a CWM site, including recovery, temporary storage, and transportation of CWM. The Safety Submission typically includes the following topics of discussion (CEHND, 1994):

- Project Description
- CWM (and/or unexploded ordnance) Field Investigative Equipment and Personnel
- Safety Procedures
- CWM (and/or unexploded ordnance) Field Investigation Methods
- Public Affairs
- Quality Control Plan
- Site Safety and Health Plan
- Site Characterization Report
- Work, Data, and Cost Management Plan
- Property Equipment Plan
- Interim Holding Facility Plan
- Transportation Plan
- Technical Escort Unit Support Plan

It is noteworthy that at least a portion of the Safety Submission requirements are redundant with CERCLA documentation requirements. In the case of OU 3, the requirement for preparing a Safety Submission was not identified until detailed design documentation had already been prepared. Identification of this requirement at an earlier stage could have resulted in combining at least a portion of the required documentation and reducing the overall effort and cost.

Those parties implementing future CWM investigations/ remediations should identify all documentation requirements at an early stage in the project and coordinate their preparation with reviewing authorities. The U.S. Army Corps of Engineers, Huntsville Engineering Center and the Project Manager for Nonstockpile Chemical Materiel can provide guidance relevant to preparation of a Safety Submission.

Management and Disposal of CWM and Associated Soil and Debris

Army Regulation (AR) 50-6 sets forth the requirements for on-site management and transportation of recovered CWM (RCWM). AR 50-6 states "Chemical agent material found buried will be classified as hazardous waste and managed in compliance with environmental laws and regulations, as applicable: Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); Superfund Amendments and Reauthorization Act (SARA); Resource Conservation and Recovery Act (RCRA)." This regulation further discusses the requirements for preparing and receiving approval for all required plans prior to "deliberate unearthing of suspect RCWM". Depending upon site-specific considerations, including applicable environmental rules and regulations, on-site destruction of RCWM (and munitions) may be considered. Off-site transportation of RCWM to an approved location will generally be accomplished by TEU. This regulation also provides significant cross-reference to other Department of Army regulations and pamphlets regarding safety and security requirements.

According to AR 50-6, "Soil suspected of contamination by chemical agents or industrial chemicals will be presumed hazardous until confirmed otherwise by laboratory analysis." On-site management and transportation (for off-site disposal) of soil and debris

suspected of contamination will be per environmental laws and regulations, as applicable.

Land disposal and/or incineration of soil and debris associated with CWM is not addressed by Federal and most State hazardous waste regulations. It is unlikely that operators of licensed hazardous waste disposal facilities will accept material generated from a CWM site because of the general nature of the material and the public and regulatory community's perception of it. CWM recovery operations should address the issue of disposal of soil and debris prior to beginning a project to ensure that all applicable environmental regulations are addressed.

The OU 3 remediation provides a unique case study in that the State of Utah has specifically accounted for CWM in its RCRA (i.e., hazardous waste) program. In the State of Utah, RCWM (i.e., recovered chemical munitions or containers) is classified as a P999 listed hazardous waste. Soil and debris excavated from a CWM site is considered an F999 or P999 listed hazardous waste, depending on the results of laboratory testing and on-site vapor/air monitoring. Accordingly, all soil and debris excavated from the OU 3 site was manifested and transported to a hazardous waste disposal facility within the State of Utah.

Specialized Training

Organizations conducting CWM investigations must ensure that their personnel are trained in the identification of CWM, and the use of specialized monitoring equipment and personal protective equipment (PPE). OU 3 operations were conducted by or under the direct supervision of TEU. Following is a brief summary of the monitoring equipment used during the OU 3 remediation:

- Miniature Continuous Air Monitoring System (MINICAMS®). This device is a continuous air monitoring device for mustard.

- Draeger Tubes. These colorimetric tubes indicate gross-level concentrations of a compound as a vapor sample is drawn into the tube using a hand-held sampling pump. Draeger tubes were used for monitoring phosgene, chloropicrin, and arsenic (lewisite and adamsite are arsenic-based).

- MONITOX. This device provides for continuous air monitoring of phosgene.

- Depot Area Air Monitoring System (DAAMS) Tubes. DAAMS tubes are used to collect time-weighted air samples at specified locations. The tubes were analyzed using an RTAP (see below) for mustard and lewisite.

- Real Time Analytical Platform (RTAP). The RTAP is a mobile laboratory equipped with a gas chromatograph for real-time analysis of CWM.

- Weatherpak® 400. This device is a meteorological monitoring station.

- MINIRAM. This device measures airborne particulates (dust).

- Flame Ionization Detector (FID). This device detects and measures organic vapors.

- Noise Dosimeter. This device continuously monitors noise levels.

A variety of PPE was also required during the OU 3 investigation and remediation. During the 1990 investigation, Montgomery Watson personnel donned "Level B" PPE, which included a supplied air system and chemically-resistant coveralls, boots, and gloves. TEU personnel donned full-face air purifying respirators and butyl rubber hoods, aprons, gloves, and boots. PPE requirements during the remediation phase were dependent on the burial area being excavated and the results of continuous air monitoring. Organizations conducting future CWM investigations or remediations should contact TEU or the Project Manager for Nonstockpile Chemical Materiel regarding appropriate monitoring and personal protective equipment.

Laboratory facilities conducting CWM analyses must also comply with significant requirements for handling CWM (including laboratory standards) and follow approved methodologies for the analyses. As these methodologies are still evolving, organizations conducting future CWM remediations should contact the Project Manager for Nonstockpile Chemical Materiel or the Edgewood Research, Development, and Engineering Center for guidance.

SUMMARY

The OU 3 site provides a unique case study in that it is the first CWM site to have completed the entire CERCLA process. The key issues and considerations highlighted above will be common to any CWM investigation or remediation, regardless of the regulatory framework under which the work will be conducted. Addressing these issues and aggressively coordinating with key organizations will ensure that all applicable requirements regarding CWM are accounted for and the project is completed in a timely manner.

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MOBILE MUNITIONS ASSESSMENT SYSTEM DEVELOPMENT

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ABSTRACT

The United States has been involved in the development, testing, storage and disposal of chemical weapons since World War I. As a result, there are numerous sites which contain the presence of chemical warfare materiel. This materiel is in the form of buried surplus munitions, munitions that did not detonate during testing and other forms. These items pose a significant human health and environmental hazard and must be disposed of properly.

The U.S. Army was tasked by the Department of Defense with the remediation of all non-stockpile chemical warfare materiel. To help comply with this tasking, the Army Project Manager for Nonstockpile Chemical Materiel is sponsoring the development of a Mobile Munitions Assessment System (MMAS). The system is being developed by the Idaho National Engineering Laboratory and Dugway Proving Ground. The purpose of the system is to inspect suspect munitions and containers, identify the fill, evaluate the fuzing and firing train and analyze samples from the surrounding area to determine if chemical warfare materiel is present. The information gained from the application of the MMAS and other systems is intended to be used to establish the best method to handle and dispose of a given munition and its contents.

The MMAS is being developed in two phases. The first phase is the development of an initial response system. This system is intended to respond to emergency situations in cases where small quantities of munitions are found and an immediate assessment is required for safety or other reasons. The Phase I system will include a radiography system to assess the fill level and the status of the fusing and firing train, a Portable Isotopic Neutron Spectroscopy (PINS) system to identify the chemical elements in the fill, computer systems to record and store data, analytical equipment to monitor the immediate environment, a weather station, communication equipment, explosive ordinance disposal equipment and all the necessary support equipment for near autonomous operation. The PINS system and the radiography systems have been used successfully in the field for several years.

The second phase of the MMAS project is the development of an assessment system that will be used at sites where large numbers of munitions are recovered. The Phase II system will include all the features of the Phase I system and will add Secondary Ion Mass Spectrometry (SIMS) to assess the presence of non-volatile chemical materiel on the surface of soil, vegetation, etc. near the munitions, phase determination to determine if the fill materiel is solid or liquid, freezing point determination to establish the materiel freezing point to aid in chemical identification and other support systems required for long term operations. The radiography equipment will likely be upgraded to real time capability. The goal of the Phase II MMAS system is to use several methods to establish the correct status and identity of the munition contents so that it can be properly handled, stored and disposed of safely.

The MMAS project is currently in the requirements development and preliminary design stage. Several system configurations were considered. These include housing the system in a truck, motor home, trailer or a shelter. Each configuration was evaluated against the operational requirements to determine which was the preferred approach. The system must be capable of being driven to a recovery site or being transported on a C-130 or larger aircraft. This requirement sets the maximum weight, length and height of the system The MMAS will be self-contained to allow for near autonomous operation. All power and other utilities will be provided. The system is being designed for operation and setup by two operators. Most of the assessment equipment will be deployed outside the vehicle by the operators and the assessments will be completed in the field. The samples for the SIMS system will be analyzed

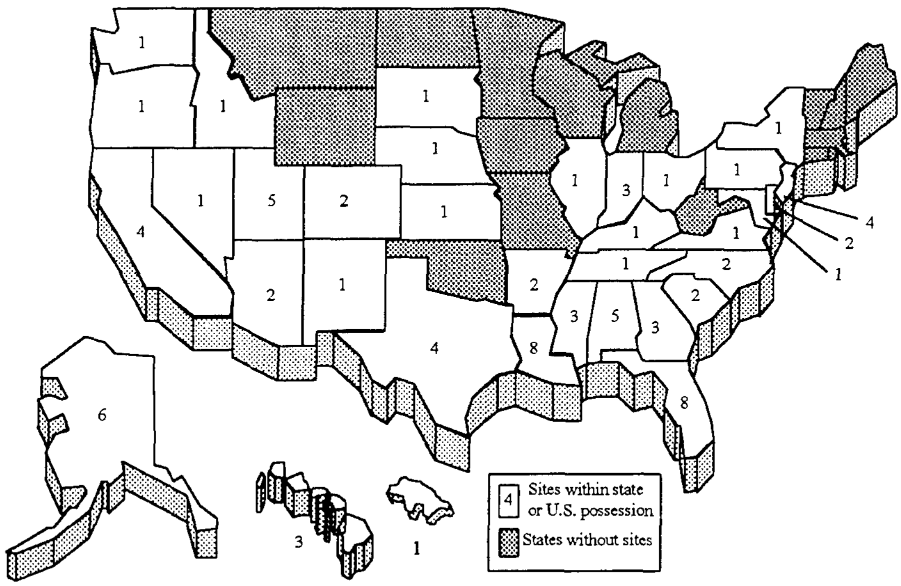

Figure 1: Potential CWM Burial Sites

inside the vehicle because of their small size and because the SIMS is less portable. The data will be transferred to the system data acquistion computers located in the trailer via transferrable media. The data will then be sent electronically from the data acquisition computers to a central data collection center for archival and review by the Munitions Review Board. The Munitions Assessment Review Board (MARB) will use the MMAS data and other data to decide on the appropriate disposal method for each item. The MMAS is expected to significantly improve safety during remediation activities and also reduce the handling and disposal costs because of correct identification of the munitions and their contents.

INTRODUCTION AND HISTORY

The Chemical Stockpile Disposal Program (CSDP) was estalished in 1986 in accordance with Public Law 99-145 to destroy the United States stockpile of lethal unitary chemical agents and munitions. In the House Appropriations Report 101-822 accompanying the fiscal year 1991 Defense Appropriations Act, Congress noted that the CSDP did not include additional chemical warfare related materiel requiring demilitarization. Consequently, Congress directed the Department of Defense (DOD) to organize an overall program so that operational responsibility for all Defense Department chemical warfare activities rested within a single office which would be fully accountable for total program execution. On March 13, 1991, the Deputy Secretary of Defense directed that the Department of the Army (DA) be fully accountable for all DOD chemical warfare related materiel destruction and designated the Secretary of the Army as the Defense Executive Agent for this purpose. In 1992, DA officially established the U.S. Army Chemical Materiel Destruction Agency (USACMDA) with the expressed mission to execute chemical materiel destruction by providing centralized management for the demilitarization and disposal of the United States stockpile of lethal chemcal warfare agnets and munitions and all non-stockpile chemical materiel (NSCM)[1].

USACMDA established two Program Managers (now project managers) for the disposal effort. The Program Manager for Chemical demilitarization was given the responsibility for the destruction of the chemical stockpile as was declared in 1985. The Program Manager for Non-Stockpile Chemical materiel was given responsibility for the execution of Non-Stockpile Chemical Materiel (NSCMP), which includes the following:

a. Chemical Warfare Materiel (CWM) buried during past disposal actions,

b. CWM recovered from either burials, ranges or the public sector,

c. binary chemical warfare munitions,

d. former chemical warfare production facilities, and

e. miscellaneous components manufactured specifically for use as or with chemical weapons, to include research and developement quantities above treaty-permitted levels[1,2].

In October 1994, the official name of USACMDA was changed to the U.S. Army Chemical Demilitarization and Remediation Activity (USACDRA), and the organization was consolidated under the U.S. Army Chemical and Biological Defense Command (CBDCOM)[1].

In December 1994, the Under Secretary of Defense, Acquisition and Technology [USD(A&T)] designated the Chemical Demilitarization (Chem Demil) Program as an Acquisition Categrory (ACAT) I Defense Acquisition Board Program. With the designation as an ACAT I Program, the name changed again, from USACDRA to the U.S. Army Program Manager for Chemicial Demilitarization (PMCD). The former Program Managers established by USACMDA were redesignated as the Project Manager for Chemical Stockpile Disposal (PMCSD) and the Project Manager for Non-Stockpile Chemical Materiel (PMNSCM)[1]. The MMAS is being developed for PMNSCM.

The November 1993 PMNSCM database indicates that CWM could have been buried in a total of 82 locations in 33 states, the U.S. Virgin Islands and the District of Columbia. Of the 82 locations, 48 are DOD installations and 34 are formerly used defense sites (FUDS). Some of these locations have multiple burial sites. As of October 1993, the total number of potential or confirmed CWM burial sites at the 82 locations is 215. This information is based on preliminary documentation research. The actual number of sites with buried CWM cannot be confirmed until site characterization studies are concluded.[2]

Munitions that may be found at these potential burial sites include 4.2 -inch and Stokes mortar rounds, aerial bombs, rockets and projectiles, and containers of agent in both 55-gallon drums and ton containers. Potential chemical agents in these munitions and containers include blistering agents [mustard (H) and lewisite (L)], nerve agents (GA, GB and VX), blood agents [hydrogen cyanide (AC) and cyanogen chloride (CK)] and choking agent [phosgene (CG)]. Many burial sites also contain other hazardous substances such as white phosphorous (a screening smoke).[2]

The MMAS will provide for an assessment of the munitions and chemicals described in the previous paragraph at the locations defined in "a" through "f" above.

REQUIREMENTS

When suspect CWM is located in the field the Army must establish the condition of the firing train and/or determine the contents of the munition or container. The equipment contained on board the MMAS is required to satisfy these needs. Specifically the MMAS equipment is required to do the following:

a. identify the munition contents (i.e. the chemical elements),

b. determine the munition fill level,

c. determine the phase (solid or liquid) of the munition contents,

d. determine the status of the munition firing train,

e. record, store, save and transmit the collected data,

f. provide weather information,

g. provide utilities (power, communications, ect.),

h. provide an integrated transportation system and working environment,

i. monitor the environment (air, soil, vegitation, etc.) at the remediation site for chemicals.

j. determine the freezing point of the chemical.

There are many important reasons to meet the requirements listed above. The most obvious reason is safety. Accurate knowledge of the status of the firing train is critical to the proper handling and disposition of the munition. Likewise, accurate identification of the chemical is important to safety and proper handling. Proper chemical identification is also important for storage of the items prior to disposal. Regulations require that certain chemicals not be stored together for safety reasons.

There are many cost considerations which require accurate identification of the chemical and determination of the firing train status. Incorrect information can lead to handling and disposal methods that are expensive and unneeded in some cases. MMAS must provide accurate and complete records to the decision makers so that proper disposition of the munitions is acheived. These records are also needed for historical reasons and to address future issues related to the remediation efforts at the various sites.

The MMAS is expected to assess the MARB build an element of trust with federal, state and local regulating agencies by providing accurate and complete information on recovered munitions and other items. The value of this trust is very significant.

DEVELOPMENT PHASES

The MMAS project is divided into two phases. This first phase (Phase I) involves developing an assessment system that consists of immediately available technology. These technologies are portable isotopic neutron spectroscopy (PINS), radiography, vapor detection (air monotoring)and data acquisition. In addition the Phase I MMAS will have the following support and utility subsystems:

a. explosive ordinance disposal equipement

b. local and cellular communications,

c. weather station and supporting hardware and software for dispersion analysis,

d. audio/video equipment,

e. electrical generators,

f. etc.

The above subsystems and associated equipment are assembled in a truck and trailer combination which is designed to travel long distances to remediation sites. In addition the truck and trailer is designed to be shipped on a C-130 aircraft.

Two Phase I MMAS systems will be built. The first system is a prototype that will be used to gain experience with the MMAS concept and the second will incorporate knowledge and improvements learned from the first system fabrication and testing. The Phase I MMAS systems are intended to be used for the initial response at recovery and remediation sites.

The second phase of the MMAS project (Phase II) involves the design and development of a state-of-the-art system that benefits from the knowledge and experience gained from the first phase. This second system would include the Phase I systems and would add Secondary Ion Mass Spectroscopy (SIMS), a revised data system, a chemical fill materiel freezing point determination system and a chemical fill material phase (solid or liquid) determination system. In addition the radiography system will be upgraded to provide real time x-ray capability. The Phase II MMAS system is intended for use at larger remediations sites where operations will continue for several months.

Phase I of the MMAS project will be conducted in FY96 to FY98. The first prototype will be delivered during February of 1997. Phase II will be conducted between FY96 to FY 00. The first Phase II prototype will be delivered during February of 1999.

SYSTEM DESCRIPTION

The preliminary design of the Phase I system is nearly complete. A trade study (See Table 1) was completed to determine the best design for the Phase I system. Four configurations were considered as follows: van/truck, Army shelter, motor home and a truck and trailer combination. A truck and trailer combination was choosen based on the the selection criteria shown in Table 1. The current vehicle design is similar to the design chosen by the team designing the Rapid Response System (RRS) for the Army. The trailer is a 24 foot 5th wheel design with a modified overhang that allows the electrical generators to be stored and transported on the truck bed. The truck is a standard Ford 1-ton which is configured and rated to tow a 12,500 pound trailer. The Phase I MMAS trailer and its contents are predicted to weigh less than 10,000 pounds. The trailer is designed with air ride suspension to reduce the shock and vibration loads on the

equipment that it carries.

The general layout of the trailer is shown in Figure 2. The back of the trailer is configured primarily for storage of the nondestructive examination equipment (NDE) which is used in the field. The NDE equipment is stored in handling containers that can be easily loaded on the truck and moved close to the remediation site. The middle of the trailer houses the computer systems, communications, instrumentation, audio/video equipement, work stations and all reference and training material. The front (overhang) of the trailer houses the heating, ventilating and air conditioning system, the air ride suspension controls and numerous instrument racks.

Lighting (12 volt and 120 volt) is provided inside the trailer. The 12 volt lighting is for temporary use only. Exterior lights are provided at each corner of the trailer. These lights are recessed so that they do not have to be removed during travel. The 120 volt lighting is powered by a 12 kilowatt generator that is located on the truck or deployed within 100 feet of the trailer. This generator also powers all the active systems located in the trailer. A 6.5 kilowatt generator is used for power at the location of the item that is being inspected. Electrical connections are provided on the outside of the trailer to allow the system to be powered by facility power.

The MMAS is equipped with a standard cellular telephone system both in the truck and the trailer. In addition the cellular phone will have access to the "Skycell" system so that there are no black-out areas in the United States. Two weather stations are included in the MMAS. One has a 10 meter mast and is located at the trailer and the other has a 3 meter mast and is located down-wind of the remediation site.

Redundant computer systems are contained in the MMAS. These systems are used to store and process data from the NDE systems and to transmit the data to a central data collection location. Audio and video equipment is manitained on-board the MMAS so that historical records of the activities can be provided.

The truck will have numerous storage compartments that will contain the majority of the standard explosive ordinance disposal (EOD) equipment. This storage location was chosen because there may be emergency cases where only the EOD equipment is required and therefore only the truck would be taken to the site.

OPERATIONAL SCENARIO

There are many different operational scenarios for the MMAS. As mentioned above, the MMAS truck could be used for an EOD activity, or NDE equipment could be removed from the trailer and transported to a site using the truck or a helicopter. The later is a very easy operation because all the NDE equipment is containerized and is easy to handle and transport. The normal expected operational scenario will be to drive or fly (on a C-130, C-141, C-17 or C-5) the MMAS truck and trailer to the remediation site. At the remediation site, the equipment will be deployed generally as shown in Figure 3.

The trailer will be deployed upwind of the remediation site and outside the hot zone. The truck will then be disconnected from the trailer and driven to the selected location for the generator that supplies power to the trailer. The truck hoist will be used to off load the generator. The electrical leads will be connected to the trailer and power will be supplied to the trailer. The subsystems in the trailer will then be powered up.

The truck will then be used to transfer the NDE systems from the trailer to a staging area, upwind, and just outside the hot zone. The NDE systems and the 6.5 kilowatt generator will be unloaded and the truck will now be available for other tasks at the site. The air monitoring equipment and the weather station will be deployed (and powered-up) at the site prior to use of the NDE equipment.

Generally, the radiography system will be the first MMAS NDE system used to examine a munition at the remediation site. The radiography system will determine firing train status and detect munition fill level if the munition is liquid filled. After the munition has been examined by the radiography system the PINS system will be used to determine the chemical elements in the fill materiel. The data obtained by PINS and from the radiograph will be input to the data acquisition computers located on board the trailer. The information on these computers can be transferred to Dugway Proving Ground or Aberdeen Proving Ground for reveiw by subject area experts. Based on the information obtained from the radiography and the PINS assay, a decision will be made on further handling and storage of the munition. If the Phase II MMAS system is being used, the operators will have the option of determining the phase (solid or liquid) of the contents and also the option of determining the freezing point of the liquid. The phase determination system and the freezing point determination systems are located in the Phase II vehicle. Knowledge of the phase and the freezing point provides additional supporting data to aid

PHASE I MMAS VEHICLE DECISION MATRIX								
10: EXCEEDS THE REQUIREMENT, 5: MEETS THE MINIMUM REQUIREMENT, 0: DOES NOT MEET THE REQUIREMENT								
ISSUE	TRUCK/VAN		MOTORHOME		TRAILER		SHELTER	
TRANSPORT ON C-141 OR 130	0	TOO TALL, 12 + FEET, C-5 OK	6	MUST BE SPECIAL BUILT, EXPENSIVE	9	DROP AXLE REQUIRED	8	ADDITIONAL HANDLING EQUIPMENT
OFF-ROAD CAPABLE	9	OK IF NOT IN MUD OR SAND	5	MINIMAL CAPABILITY	8	COULD BE TOWED BY A TRACKED VEHICLE	4	SPECIAL TRUCK, CRANE TO UNLOAD
WORKING SPACE	8	24' VAN LENGTH 8' WIDTH	9	UP TO 35' LENGTH, 7' WIDTH	10	UP TO 40' LENGTH, 8' WIDTH	10	MANY LARGE SIZES AVAILABLE
TOWING (GENERATOR)	10	NO PROBLEM WITH TOWING	8	LIMITED TOWING	0	NOT CAPABLE	6	TRANSPORT VEHICLE COULD TOW
OPERATIONAL CONVENIENCE	10	SELF-CONTAINED	10	SELF-CONTAINED	7	TRACTOR REQUIRED	3	TRUCK AND CRANE REQUIRED
INITIAL COST	8	$50K	3	$100K	10	$30K	3	$100K ARMY $50K COM.
OPERATING COST	7	MAINTAIN TRUCK	7	MAINTAIN MOTORHOME	10	TRACTOR USED WHEN REQUIRED	5	TRUCK AND CRANE REQUIRED
DELIVERY	8	4-6 MONTHS	5	6-8 MONTHS	9	3-6 MONTHS	8	4-6 MONTHS
EASE OF MODIFICATION	8	RECENT EXPERIENCE	8	SAME AS TRUCK	8	SAME AS TRUCK	6	EXTERNAL STRUCTURE
VIBRATION DAMPING	9	AIR RIDE SUSPENSION POSSIBLE	10	AIR RIDE SUSPENSION ROUTINE	6	SPRING SUSPENSION TYPICAL	5	SPECIAL TRUCK REQUIRED
SITE TRANSPORTA-TION	5	NOT USABLE DURING OPERATION	5	NOT USABLE DURING OPERATION	10	CAN BE USED AT ANY TIME	0	NO VEHICLE
TOTAL:	82		76		87		58	
THE ISSUES ARE NOT WEIGHTED IN IMPORTANCE.								

Table 1:Vehicle Configuration Selection Criteria

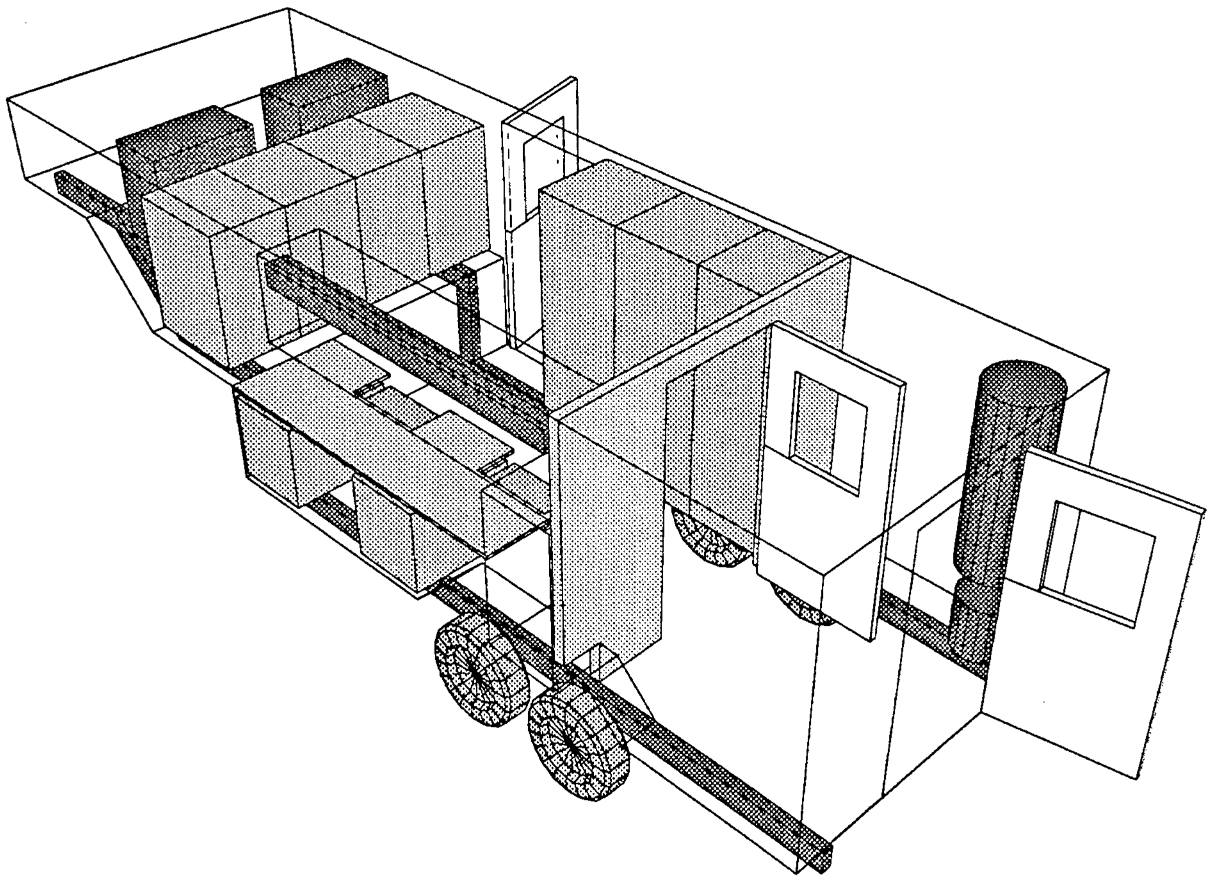

Figure 2: General Layout of MMAS Trailer

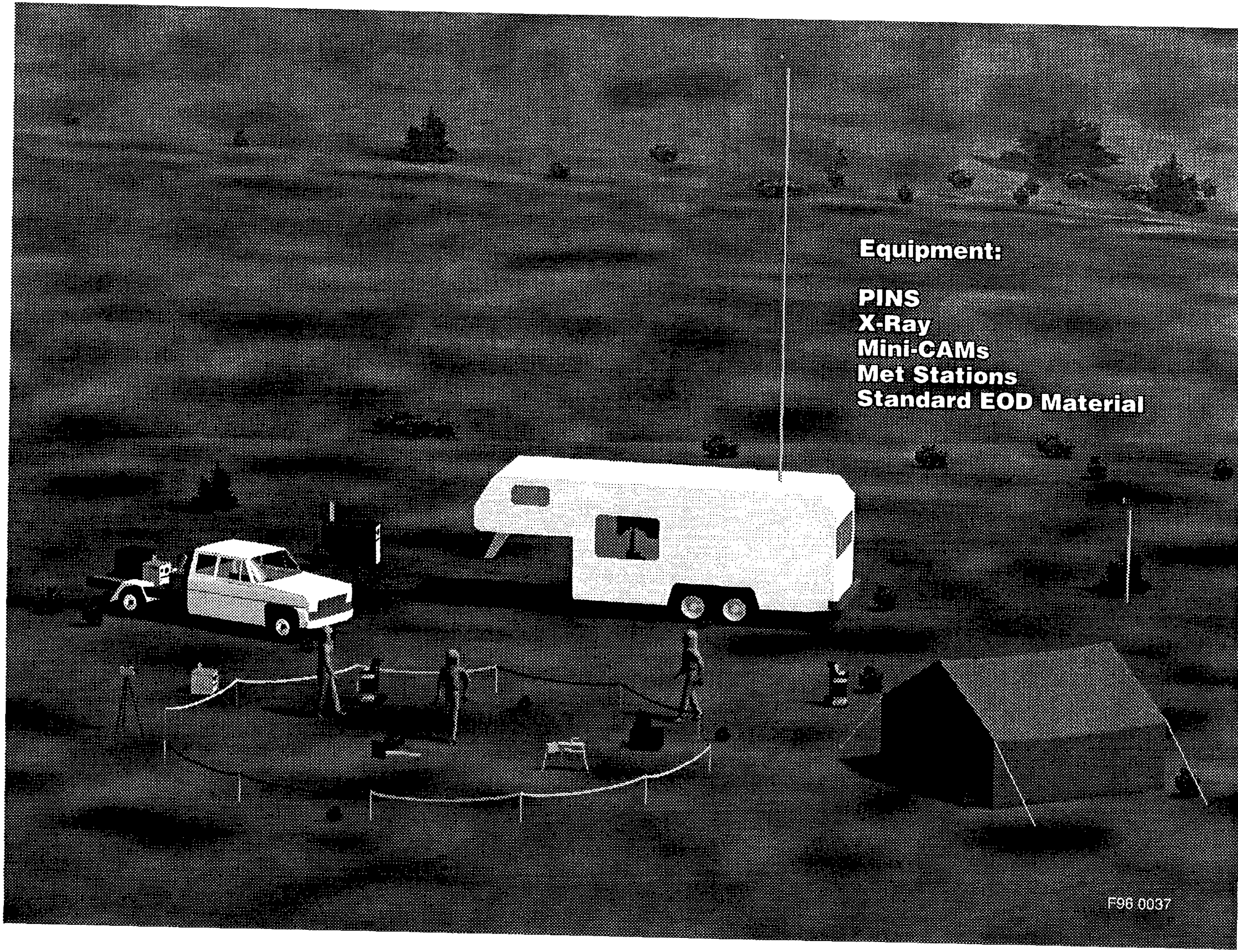

Figure 3. MMAS Deployment Scenario

in the correct identification of the munition's contents. Data from these systems is also fed to the data acquisition computers.

SIMS will be used to test the soil and vegetation near the munition for non-volatile chemicals. Data from the MMAS weather station, GPS station and the air monitors is continuously routed to the data acquisition computers during a site remediation activity. This information, along with the information form the NDE systems provides a historical record of the activity for future use.

Exit from the site proceeds approximately in reverse of the setup. Monitoring of the equipment for chemical contamination is required as is cleaning of some of the equipemnt that is used. Standard equipment and materials are used for this operation.

The MMAS can operate nearly autonomously at a remediation site. There are two exceptions to this however. The MMAS does not have equipment on board to recharge the SCUBA tanks and it will be necessary to obtain gasoline for the generators. The truck is available to obtain these items from local vendors or from the Army Post if the operation is occurring there.

STATUS

The MMAS project is in the preliminary design stage for the Phase I system. The truck and trailer have been purchased as well as numerous other equipment items. Modifications to the truck will begin in March of 1996 and assembly of the trailer will begin in April of 1996. Testing of the Phase I prototype will begin in October of 1996 at Dugway Proving Ground. Delivery of the first Phase I prototype to the Army is scheduled for February of 1997.

SIMS, phase determination, freezing point determination, real time radiography and improved air monitoring will be added to the MMAS Phase II prototype. Research and developemnt has started on these systems and will continue through FY96 and FY97. Assembly of the Phase II prototype will begin in FY98. The Phase II prototpye will be delivered to the Army in February of 1999.

CONCLUSIONS

The MMAS systems will provide the following information on recovered chemical weapons material and the remediation site:

a. chemical elements in the fill,

b. munition fill level,

c. phase (solid or liquid) of the fill materiel,

d. freezing point of the fill material,

e. status of the firing train

f. volatile chemicals in the air

g. non-volatile chemicals on soil, vegetation, etc.

h. weather data

All the data from the MMAS systems will be recorded, stored and saved so that accurate historical records are maintained on all items. In addition the data will be contained in a format that can be readily used by the Munitions Review Board.

The MMAS provides an integrated transportation system and working environment for the operators. All utility and communication equipment is provided to allow nearly autonomous operation at a remediation site.

The MMAS will be an extremely valuable tool for use at chemical weapon materiel remediation sites. Knowledge gained from the NDE systems will allow the Army to make more informed decisions on the disposition of recovered chemical weapons materiel. This will lead to improved safety, reduced costs, reduced remediation time and increased confidence in the remediation process being conducted.

REFERENCES

1. U.S. Army Program Manager for Chemical Demilitarization, Non-Stockpile Chemical Materiel Program Implementation Plan, August 1995.

2. Program Manager for Non Stockpile Chemical Materiel, Non-Stockpile Chemical Materiel Program, Survey and Analysis Report, November 1993.

DRILL AND TRANSFER OPERATIONS OF SUSPECT CHEMICAL FILLED MUNITIONS AT ABERDEEN PROVING GROUND

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ABSTRACT

As a result of Installation Restoration (IR) activities at Aberdeen Proving Ground (APG), the inventory of recovered suspect chemical filled munitions continues to grow. With permitted storage space at a premium, emphasis has been placed on assessment and disposal of those items which do not contain energetic components. This approach will provided the necessary relief while a full-up system to address explosively configured munitions is being designed and constructed. These operations will also serve to validate non-intrusive assessment technologies such as the Portable Isotopic Neutron Spectroscopy System (PINS).

BACKGROUND

The Edgewood area of APG has been the Army's primary focus for research and development activities associated with chemical warfare materiel since 1918. Until the 1970s a wide variety of munition types including rockets, projectiles and bombs were filled and tested with both classic chemical agents as well as many different experimental compounds. Large areas were used as impact zones for open air tests. History also indicates that surplus munitions were routinely buried on the installation upon the cessation of testing. In 1990, the Edgewood Area of APG was added to the National Priorities List in accordance with the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). As a result, Records of Decision (ROD) are being pursued for the eventual total remediation of APG. IR activities are expected to result in the recovery of large numbers of unexploded ordnance containing both conventional and chemical fills.

MUNITION ASSESSMENT

Recovered munitions are first evaluated by the U.S. Army Technical Escort Unit Explosive Ordnance Disposal personnel. If the item is deemed safe to move and characteristics of the munition indicate that it may contain a chemical fill, the item is overpacked and put into storage until further non-destructive assessment can be accomplished. The munition is first x-rayed to determine if the round is explosively configured. This technique also provides valuable information on the characteristics of the fill material such as phase and fill level. The item is then assayed using PINS which was developed by the Idaho National Engineering Laboratory (INEL). The PINS utilizes a neutron source to bombard the contents of the munition with free neutrons. When the nucleus of an element captures a free neutron, it emits gamma radiation which is unique to that particular element. These signature gamma ray peaks are then matched to known energy levels for elements of interest and the key elements of the fill material are thereby identified. All data collected on each munition is collated and reviewed by the Munition Assessment Review Board (MARB). The MARB is comprised of individuals which are experts in the field of munition design and operation, radiographic interpretation, PINS data interpretation, and the weaponization of chemical warfare materiel. Data available may include known historical information, radiographic interpretation, and results of the PINS analysis. Using all available data the MARB makes a recommendation on the final disposition of each item.

CHEMICAL TRANSFER FACILITY (CTF)

Munitions which are deemed safe to access and are suspected to contain a chemical fill are transported to the Chemical Transfer Facility (CTF) for processing. The CTF, located in a high security area, is permitted by the state of Maryland, for the storage and treatment of hazardous substances, including chemical warfare materiel. The entire facility is serviced by a filtered ventilation system. All rooms dedicated for agent storage, laboratory operations, agent transfers from bulk to smaller containers and processing of munitions are kept under engineering controls. The entire facility is monitored by a continuous, real-time low-level monitoring system.

CHEMICAL AGENT TRANSFER SYSTEM (CHATS)

Drill and transfer operations are conducted at the CTF in the Chemical Agent Transfer System (CHATS) (see Figure 1). The CHATS is a fully self-contained system that employs a positive stop, remotely controlled pneumatic drill to access the munition body. Glove ports are provided to interface the operator during manual portions of the operation. The CHATS design includes a dedicated redundant gas/particulate filtration system that maintains the interior working volume at a negative pressure while over 20 air changes per hour are passed through the system. Utilities provided to the CHATS include compressed air, vacuum, hot and cold water, steam and decontamination solution. The CHATS design also includes a waste collection system to collect liquid effluent from the decontamination/rinsing process.

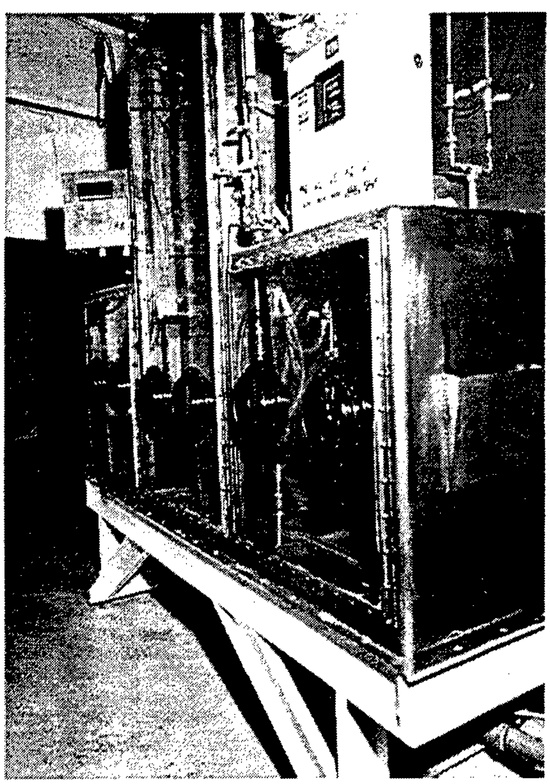

Figure 1

DRILL AND TRANSFER PROCEDURES

Chemical operators dressed in a Army level B protective posture (coveralls, boots, gloves, protective mask, butyl rubber apron) carefully remove the munition from it's overpack container. Special attention is made to ensure that a leaked has not developed during transport and storage. If it is determined that the item is leaking, it will be returned to the overpack for later processing as current approved procedure do not provide for processing of "leakers" in the CHATS. The entrance door to the CHATS is opened and the item is manually loaded and secured on to a wheeled cart located on the "cold side" of the system. The entrance door is secured and the operators, utilizing the glove ports, open the interior door accessing the drill and transfer area. The transfer cart containing the munition is then manually transferred into place and secured below the pneumatic drill. The interior door is then secured. Using the radiographs provided as a result of x-ray assessment of the item , the munition is marked in two places for drilling out of the vicinity of the burster. The drill is then lowered into place just above the access point. The operators exit the area and proceed to the remote drilling station where they activate the drill and observe the operation via closed circuit television. The drilling operation is also recorded on video tape. Because of the thickness of the walls of many of the munitions processed, it is often necessary to first drill a pilot hole followed by a bit to effect a 0.5" opening. Upon completion of the first access point, the munition is manually moved into place and again secured for drilling of the second area. The second opening is made in the item acts as a vent to ease the transfer and decontamination process. Upon completion of the drilling process, a sample is extracted and placed in an appropriate sample container. M8 detector paper is used as a preliminary check for the presence of chemical agent in the liquid fill. A blue band colorimetric tube is also used as an additional check for the presence of agent vapor. The sample container is then sealed, the outside decontaminated and placed in a fiber tube for transport to the laboratory for subsequent analysis. The remainder of the munition contents is then transferred by vacuum to a Department of Transportation (DOT) certified shipping container and sealed. After sealing the outside of the container is checked with M8 paper to insure no agent contacted any exterior surface. Decontamination is conducted if needed. The interior of the munition is then filled with appropriate decontaminating solution, allowed to sit to achieve the required contact time and then manually emptied into the CHATS waste collection system. This procedure is followed by a triple rinse of water and the access holes are tapped and sealed with teflon plugs. The exterior of the item is then decontaminated, rinsed with water and dried. The munition, the fiber tube containing the NMR sample and the DOT container is then transferred back to the "cold side " of the CHATS through the internal access door. The items are monitored one final time with a M256 detector kit to verify that no agent is present prior to removal from the CHATS. The munition body is again double wrapped in plastic and returned to it's overpack to await laboratory

analysis of the sample. The final disposition of all fill material is handled in accordance with an approved waste management plan. Generally, any chemical agent that can be purified by distillation such as G-series and H-series agents, will be reclaimed and returned to the research and development inventory. Non-surety wastes are disposed of in accordance with all applicable federal and state regulations. Munition bodies are thermally treated and reclaimed as scrap metal.

ASSESSMENT RESULTS

As of February 1996, 77 munitions have been processed through the CHATS. Data regarding the munition type, fill as determined from historical records, fill determined by the PINS assay and actual fill from laboratory analysis of samples is presented in table 1. Of particular importance to the safety of drill and transfer operators is the ability to accurately predict the fill material through non-intrusive methods such as PINS. In 57 cases a direct comparison of the actual fill as determined by laboratory analysis and PINS assay can be made. Of those 57 cases, PINS successfully predicted the actual fill of 34 munitions , a 59.6% correct identification rate. The majority of incorrect PINS identifications involved relatively small 75mm projectiles. Excluding the 75mm projectiles, PINS correctly identified the fill of 92% of the munitions assayed. INEL has recently modified the PINS configuration to improve sensitivity for small projectile (see Reference). It is important to note that although the PINS assessment technology hold much promise for enhancing the safety posture of drill and transfer operations, this technique is still considered experimental in nature. Data generated is being provided to INEL personnel on a continuous basis. Valuable lessons learned are providing a basis for improving the reliability of this assessment method through modification of equipment and procedures.

CONCLUSIONS

Drill and transfer operations on-going at APG are an important first step to dealing with the large numbers of unexploded ordnance that is expected to be recovered during remediation efforts at APG. Although a system that a capable of processing both explosive and non-explosive munitions is required, current operations are freeing up valuable storage space and allowing the IR program to continue until a facility that is capable of processing explosive items can be brought on line. Data generated as a result of these operations are also serving to further refine and validate non-intrusive assessment technologies such as the PINS.

Reference: A.J. Caffrey, et al., "Field Applications of the PINS Chemical Assay System for the Identification of Unexploded Chemical Warfare Bombs, Containers and Projectiles."

Nomenclature	Historical Fill	MARB Fill	Actual Fill
Mortar, 4.2"	ND	HD	Dichlorobenzene
Bomblet, M125A1	ND	NKE	Ethylene Glycol
Bomblet, M125A1	ND	NKE	Ethylene Glycol
Bomblet, M139	ND	NKE	Ethylene Glycol
Stokes, 4"	ND	NKE	Water
Rocket, M155mm M60	ND	NKE	Ethylene Glycol
Rocket, M55	ND	NKE	Ethylene Glycol
Livens	ND	NKE	Empty
Projectile, 105mm	ND	NKE	Empty
Projectile, 155mm	ND	NKE	Ethylene Glycol
Projectile, 155mm	ND	NKE	Empty
Projectile, 155mm	ND	GB	AL/Mag Salts
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	Weak Nitrogen	Nitrobenzene
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	Empty
Projectile, 75mm	ND	NKE	Nitrobenzene
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	TNT
Projectile, 75mm	ND	NKE	TNT
Warhead, M56 (M55)	VX	GB	GB
Warhead, M56 (M55)	VX	GB	GB
Warhead, M56 (M55)	VX	GB	GB
Warhead, M56 (M55)	VX	GB	GB
Warhead, M56 (M55)	VX	GB	GB
Warhead, M56 (M55)	VX	GB	GB
Warhead, M56 (M55)	VX	VX	VX
Warhead, M56 (M55)	VX	VX	VX
Warhead, M56 (M55)	VX	VX	VX
Warhead, M56 (M55)	VX	VX	VX
Warhead, M56 (M55)	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	GB
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	GB
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	GB
Projectile, 175mm	VX	VX	VX
Projectile, 175mm	VX	VX	VX

KEY:
ND = No Data
NKE = No Key Element

TABLE 1

HYDRO ABRASIVE CUTTING AS AN OPERATIONAL EOD TECHNIQUE

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INTRODUCTION

The aim of the following presentation is to introduce to you aspects of Explosive Ordnance Engineering work that is conducted at DTEO Shoeburyness, and in particular the development of a new portable Hydro Abrasive Cutting System, the "MARLIN", for use on EOD operation.

ORGANISATION

DTEO Shoeburyness is part of the United Kingdom Defense Evaluation and Research Agency. DERA is a new organisation which was created in April 1995. It was formed by bringing together virtually all of the UK Ministry of Defences' non-nuclear science and technology resources and it provides world class scientific advice, innovative engineering solutions and a broad range of technical services to Governments and Industry throughout the world. With a business turnover of around $1.5 Billion per annum, DERA now represents the largest organisation of its kind in Western Europe.

DERA is organised into four division. The Defense Research Agency (DRA), the Chemical and Biological Defence Establishment (CBDE), the Centre for Defence Analysis (CDA) and the Defence Test and Evaluation Organisation (DTEO). The Land Capabilities Sector of DTEO is primarily responsible for the Proof and Testing of Guns, Missiles, Weapon Systems and Ammunition for the three services, government departments and commercial industry, together with Demilitarisation Operations for the UK Ministry of Defence.

TOPOGRAPHY AND HISTORY

DTEO Shoeburyness is located at the mouth of the River Thames about 35 miles East of London. The site comprises a total land mass of 7500 acres, which extends to 35000 acres for 4 hours at low tide. The Sea Danger Area is large and has access restricted by Bye Laws; it is policed by the Ranges' own hovercraft. This coupled with an ability to close airspace to 60000 feet, gives Shoeburyness unique capabilities in several areas, particularly for the Over Water Recovery of fired munitions.

Shoeburyness has a long history in the development of weapon systems and the formation of EOD techniques and procedures. Artillery experiments at Shoeburyness started in 1849 in the Old Ranges, as a result of difficulties with safety areas on Plumstead Marshes. The British School of Bunnery was established in 1859, which then evolved into the School of Artillery. By the late Nineteenth Century the land area had expanded into what is now known as the New Ranges, and the advent of the First World War saw a further increase in land area with the purchase of Foulness Island.

It may be of interest to you, that the secrets of the German Second World War Magnetic Mines were unraveled at Shoeburyness. The Germans commenced their air delivered mine offensive on 17 November 1939, and one week later, on the night of 23/24 November 1939. two mines were conveniently dropped into the tidal sands of the establishment by a German Heinkel Bomber. They were neutralised by two Royal Navy officers, and the resultant degaussing program that quickly evolved, ensured that shipping losses to these weapons were kept to a minimum. Unfortunately history does not relate the fate of the German pilot who inadvertently compromised on the his countries greatest secrets.

CONVENTIONAL MUNITION DISPOSAL OPERATIONS

In addition to its Demilitarisation of surplus ammunition and explosives, DTEO Shoeburyness has an ongoing requirement to identify, and then dispose of, large caliber munitions from all three services, that have been recovered as a result of field EOD operations. These munitions have been rendered or declared safe by an EOD team, and are then brought to Shoeburyness for disposal. They could vary from large aircraft bombs to sea mines.

More regularly, old training munitions are recovered, and it is often impossible to declare them Free From Explosive by visual inspection alone. Recently in Australia, a supposedly inert Mk5 Sea Mine was being demilitarised by the use of a hot cutting technique to cut the concrete filled body into pieces. Unfortunately, in order to inert the mine during the 1960s, the explosive filling had been steamed out before the mine was refilled with concrete. The steaming did not totally remove all the explosive filling, and a thin layer was trapped between the mine casing and the concrete. When the thermal energy hit this trapped explosive 30 years later, there was an event which injured the operator. If only for this reason alone, old training munitions should always be treated with care until it can be confirmed that they are really Free From Explosive (see Photograph No. 1)

The only method available to Shoeburyness was to destroy these munitions by Open Detonation techniques. This option is logistically inefficient, expensive in materials and a range time, and causes several acoustic pollution. Therefore, alternative methods of investigation and access were investigated.

It was assessed that a hierarchial system of interrogation, utilising combinations of X-Ray and Neutron Absorption technology could not provide a 100% guarantee of identification of the wide range of munition fillings that have been used over the last 150 years. The use of Ultrasonic identification systems was also discounted as they are still in the early stages of development. (Timothy 1995)

DTEO Shoeburyness has recently laid a contract with Colt Industrial Services Limited of Hull, for the design, development and production of a Hydro Abrasive Cutting System to support the APE 1236 Rotary Kiln technology of Project AVOCET. This system has the capability of gaining access to munitions of 155mm caliber and below, on a production basis, before they are disposed of by other techniques. The system consists of three ISO - Containers, but is unsuitable for use on Aircraft Bombs and Sea Mines etc. due to its design for production operation (see Photograph Nos. 2 and 3).

It was therefore decided to investigate with Colt, whether it would be feasible to produce a portable system that was suitable for use on field EOD operations. The design work commenced in June 1995, and the first prototype trials took place on 19 September 1995. These trials were successful, and the first production model for EOD operations at DTEO Shoeburyness was completed and tested in January and February 1996 (see Photograph No. 4).

EVELOPMENT OF HYDRO ABRASIVE CUTTING (HAC)

Before explaining the system specifications and the initial trials results, it would be useful to explain the technology of Hydro Abrasive Cutting and its development with the UK. The advantages of Hydro Abrasive Cutting over the competitive technology of Lasers, Plasma and Ox-fuel are that HAC is a heat and spark free erosive process that produces no vibration. It has no effect on the internal structure or properties of the target material, and can obviously be used with a large degree of safety in hazardous environments.

Plain Water Jet Cutting was developed in the 1970s utilizing purely the power of the water to produce the cut. These systems operated at very high pressures, and there are still many around in the manufacturing industries. Initial development work of Hydro Abrasive Cutting systems was conducted by Cranfield University in the early 1980s.

Although the work had been previously carried out in the 1970s, in both the UK and USA, into the cutting of materials, with both high and ultra high pressure systems, it was not until later that the principles of the "Entrainment" and "Direct Injection" systems became fully understood and technically practicable. The initial systems that utilized the Direct Injection process operated at very low pressures, and the cutting efficiency was still extremely poor. This is why a large proportion of research, on both sides of the Atlantic, was still directed towards the development of ultra high pressure systems in the regions of 40000 p.s.i.(c.a. 3000 BAR) and above, and mainly concentrated on the entrainment system.

There were two practicable technical solutions available. One system, where the abrasive was added to the high pressure water in the cutting head at atmospheric conditions. The high pressure water flow acts as an ejector jet pump, and sucks the air/abrasive mixture into the outside of the water jet, which induced heavy wear in the nozzle. This is commonly known as Entrainment Abrasive Water Jet Cutting (EAWJC). Entrainment systems commonly operate at around 40000 to 60000 p.s.i. (c.a. 3000 to 4000 BAR). Over 1000 such systems have been installed in manufacturing industries, of which the majority are used to cut complex shapes out of a variety of materials. EQWJC is an inefficient process in which up to 80% of the energy in the water jet is dissipated, and up to 50% of the abrasive is broken down during the mixing process. (Miller 1995) This system also has significant restrictions for its use with explosive ordnance, which will be discussed later.

The alternative to this was the system of suspension or direct injection water jet cutting which was developed by the Cranfield based British Hydro Research Group (BHR Group). In this case the abrasive is generated in the water slurry at pressure, and the resultant water/abrasive slurry is then passed into the main water flow, before being directed through a specially designed nozzle, and are thereby deflected towards the centre of the water flow. This means that a film of water can be created between the remainder of the nozzle and the abrasive during the acceleration phase, which minimizes wear in the rest of the nozzle. The particle velocity is virtually the same as that of the carrier fluid and can be easily calculated. (Bailey 1994) This method is known as DIAJET®, and you will hear all direct injection systems now commonly referred to as DIAJET® systems.

Towards the mid 1980s, the theory had been proven in the UK that water at pressures of 3000 - 8000 p.s.i. (c.a. 214 - 570 BAR), with added abrasive, was capable of cutting most materials without inducing heat or sparks. However, this viable, working DIAJET® system was still extremely crude, and far from being capable of deployment as a production technique.

However, in terms of the application of Hydro Abrasive Cutting to operations in high risk areas, the DIAJET® system, at the lower pressure range, was assessed as being the safest, most efficient and reliable system, available at that time, for these reasons:

1) DIAJET® utilizes a single line hose; there is no need for a separate hose to carry the abrasive to the nozzle as in the entrainment system. This reduces the complexity of the cutting head, thereby also reducing the complexity of the required manipulation systems.

2) In DIAJET® there is no risk of a spark being created from a dry abrasive ignition. If the water flow stops, so does the abrasive. In the entrainment system it was possible for the water flow to cease, whilst dry abrasive was still being directed at the target at high pressure. The entrainment system has secondary effects, in that a percentage of the abrasive particles have a significant radial velocity component due to the highly turbulent mixture of air, water and abrasive. (Miller 1995) Any one of these effects could lead to the creation of sparks, and this is obviously an unsafe option when you consider the applications for which Hydro Abrasive Cutting was being developed. This parking can be negated by using the cutting head submerged in water, but this reduces the available applications and adds complexity to the manipulation systems.

3) The lower pressure DIAJET® system utilizes a standard, positive displacement Triplex or Diaphragm Pump, that has the capability to operate on all standards of water supply, including sea water. The intensified systems, that are still available, are adversely affected by poor water quality, and generally require a water filtration system, (down to as low as 1 micron), to maintain their efficiency levels. This creates extra cost and adds bulk to the complete system.

4) Direct injection systems offer a neater and more compact solution to the total equipment requirements. The same equipment can also be used to flush out the explosive material, with slight modifications to the manipulation systems.

5) The temperature gradient at the cutting face of the target materials during DIAJET® cutting has been measured, and the maximum temperature rise if typically in the region of 10.5°C whilst cutting in air. (Bailey 1994)

By 1986, a system had been developed in the UK that was robust, reliable and safe to use; although at this stage no manipulation system had been designed to guide the nozzle in the target area. The initial manipulation systems were operated with a small 9 Volt electric power supply; these were obviously counter-productive in terms of utilizing the technology in a hazardous area, but they did provide much needed data into the requirements of the manipulation system.

The development of a hydraulic manipulation system in 1987/88, solved the problems of manipulation, and this meant that the Hydro Abrasive Cutting System had a real future in cutting of materials in hazardous areas, including under water. An accurate and reliable system had been developed, that opened up the opportunities for the use of Hydro Abrasive Cutting in Petro-chemical installations, Oil platforms, Nuclear Plant Disassembly and Munition Demilitarisation. Since 1987/88, the lower pressure DIAJET® system, designed and manufactured by COLT Industrial Services Limited, has been regularly used in many high risk and hazardous scenarios from the repair of damage after an explosion in an Oil Refinery to the capping of the Oil Well Fires in the Post Gulf Conflict Kuwait.

There is still an ongoing discussion in the Hydro Abrasive Cutting community as to the relative merits of high versus lower pressure direct injection systems. The higher pressure DIAJET® systems at 10,000 to 30,000 p.s.i. (c.a.

700 to 2,000 BAR), offer the potential for the use of smaller nozzles and smaller abrasive particles with a resultant increase in cutting efficiency. However, higher pressure pumps, harder nozzles, and more complex feed and manipulation systems are then required to support this increase in cutting efficiency. Therefore at the moment, the lower pressure systems are more practical, more economic to procure and more reliable to operate. Until the technology of the higher pressure DIAJET® systems is proven commercially, and "safe" operating envelopes are fully developed for cutting explosives at these high pressures, their use should be considered in line with the laws of dimishing returns. (BHR Group is currently conducting a research programme into the technology of "high pressure" DIAJET® systems). The problem with the high pressure systems is that the impact velocity of the water at these high pressures could be high enough to induce an explosive event in the more sensitive explosive types.

Research to date by both the Defence Research Agency at Fort Halstead and the Royal Military College of Science, Shrivenham has proved that cutting at lower pressures is in the "safe" operating envelopes of direct injection systems, with a considerable safety margin. The impact velocities are low, in the order of 200 to 300 m/s, which is well below the critical velocities of 1,500 m/s. Therefore, the differences in cutting efficiency and time and safety versus cost reliability, convinced DTEO Shoeburyness to adopt the commercially proven lower pressure direct injection systems.

SYSTEM	PRESSURE (BAR)	IMPACT VELOCITY ($M.SEC^{-1}$)[*]
AVOCET (4,500 p.s.i.)	321	253
MARLIN (3,500 p.s.i.)	250	224
Typical High Pressure System (32,200 p.s.i.)	2,300	678
Typical Ultra High Pressure System (70,000 p.s.i.)	5,000	1,000

[*] Velocity ($m.sec^{-1}$) - (c.a). (200 x Pressure (BAR)$^{\frac{1}{2}}$)
(Formula obtained from the Technical Department of WOMA Gmbh)

Figure 3 - Comparison of Impact Velocities of DIAJET Type HAC Systems

There is one possible disadvantage to the use of HAC for the preparation of ammunition and explosives, and that is the possibility of grit sensitisation. As the abrasive is used to cut the exposed bare explosive, after penetration of the target body, it forces its way into the explosive and creates grit sensitive points. If the explosive is handled roughly, then there is a possibility of some form of initiation due to induced friction between the spent abrasive and the explosive. This disadvantage can be greatly negated by washing the explosive after cutting with high pressure water, and then exercising the usual safety precautions involved with the movement of bare exposed explosives.

DEVELOPMENT OF MARLIN

In July 1995, DTEO Shoeburyness produced a Statement of Requirement for the design, development and manufacture of a truly portable Hydro Abrasive Cutting System; this was to be known as Project MARLIN. The system had to fall within the technical specifications shown in Figure 4.

Operating Pressure	3500 p.s.i. (250 BAR)
Flow Rate	21 litres/minute
Nozzle Diameter	1.8 mm
Gross Weight	< 1000 kg
Maximum Dimensions	< 1000 x 700 x 600 mm

Figure 4 - 'MARLIN' Technical Specifications

The prototype 'MARLIN' was ready for its initial trials by early September 1995. It was decided that for trials of the MARLIN system, that in inert aircraft bomb would be attacked first, in order to gain experience of the system before attacking a live munition. The tripod rig for the prototype was designed to have the flexibility to attack different munition types and sizes. Once this experience had been gained then an 8" HE Shell would be attacked for the first live trial of the system.

An 8" HE Shell was selected for the first live trial of 'MARLIN', because it has a very thick casing, and is filled with TNT which is more sensitive than the majority of military explosives. In other words, it was the worst case munition that was readily available for use on these trials.

The cutting time to access for the inert aircraft bomb was 17 minutes, however the trial time was nearer to an hour due to the requirement to stop cutting in order to refill the pressure cylinder with abrasive. The production system has been designed with two pressure cylinders, so that continuous cutting is possible. The operator now only has to switch to the second cylinder whilst the first cylinder is refilled with abrasive. It is easy for the operator to know when the abrasive requires refilling by the performance of the water:

1) When the water is reflected upwards it means that the system is cutting the target.

2) When the water is spread out in a flat circular disc around the target area, it means that there is no cutting action taking place due to the requirement to change over the abrasive mixing cylinders.

3) When there is no reflected water, but just a "bubbling" action, then it means that the target munition has been penetrated at that point.

OPERATIONAL TECHNIQUES

The current Render Safe Procedures for fuze immunisation, and the subsequent removal of the explosive filling of an unexploded bomb (UXO) were developed in the UK during World War II. These involve various fuze immunisation techniques, after which there is still a requirement to extract the fuze.

Once the fuze has been immunised and extracted, often at great risk to the EOD operator, the explosive filling is accessed by the Trepanning technique, which utilises a slow rotational engineering milling cutter to cut through the bomb casing. This creates both friction and heat which can be reduced by the constant application of a lubricant. Other techniques involve the use of Ballistic Attack methods which often have a secondary deflagration, or even detonation, effect.

Once the explosive has been exposed, the filling can be removed by steaming. This is a suitable technique for the removal of TNT type materials, as TNT has a melting point of about 80C; however it is not suitable for the removal of more modern PBX or was composition explosives. A current alternative to steaming is the use of high temperature incendiary thermite.

The 'MARLIN' system has many advantages over the more traditional techniques:

1) The UXO can be attached remotely, possibly without the requirement for prior fuze immunisation. The UXO can be attacked at point away from the fuze, and the lack of heat, sparks or any significant vibration combined with the low impact velocity means that it is possible that neither the fuze of main filling is initiated.

2) Once access has been gained to the munition, the filling can ben be flushed out utilising the same 'MARLIN' system, (however the manipulation to achieve this option is still under development). This filling can then be later destroyed utilising a Low Temperature Thermite Charge that will be briefly discussed later.

3) The only explosive left in the UXO is now the fuze and booster/gaine system. This can be destroyed in situ with a minimal danger area, unless there is still a requirement to try and neutralise the fuze for intelligence purposes. However, as an Electric Detonator has been attacked longitudinally by Hydro Abrasive Cutting without an explosive event, there is a chance that the fuze could be safely removed utilising 'MARLIN', although there is obviously a chance that it may initiate. (More research is required in this area).

4) The option that is available now, if for the part of the bomb that contains the fuze to be secured to negate all movement. The remainder of the bomb can then be cut away from the fuzed area using a linear or circular manipulator; this can then be destroyed using the low temperature thermite. The remainder of the UXO that contains the fuze can ben also be attacked by a separate low temperature thermite; this will burn away a proportion of the explosive until the sensitive explosive filling of the fuze is initiated by the heat. In this case the resultant explosion will be a fraction of that of the full charge, and can be contained by tamping.

MARLIN has both Military and Commercial applications where cutting is required to be conducted in hazardous areas.

Military Applications	Conventional Munition Disposal
	IED Disposal Access
	Counter Terrorist Search Assess
	Demilitarisation Operations
Commercial Applications	Construction Industry
	Damage Control on Ships
	Fire and Rescue Service Operations
	Mining
	Nuclear Plant Dismantling Operations
	Offshore Gas and Oil Platforms
	Petro - Chemical Industry

Figure 5 - 'MARLIN' Applications

The complete 'MARLIN' system for UXO disposal consists of the pump and power unit, the manipulator and the manipulator control mechanism. 'MARLIN' can be transported on a small trailer or in the back of a small van. It is also possible to reduce the system size, if the Power Take Off unit on the vehicles is utilised. The pump unit, control panel and pressure cylinders can then be mounted in the rear of the vehicle. This reduces the complete system size by 50%.

Initial trials have also been recently completed as to the feasibility of mounting 'MARLIN' onto a Remote EOD vehicle. The Mark 8 WHEELBARROW was used for these trials, and the initial indications are that the system shows considerable potential as a non explosive access weapon. It is intended to conduct more trials work in this area to fully evaluate the IEDD potential of the system.

LOW TEMPERATURE THERMITE

A unique Low Temperature Thermite has been developed and trialled at DTEO Shoeburyness. As part of the demilitarisation programme, alternative methods to the Open Detonation of munitions were investigated. This led to the use of the LTT as a standard demilitarisation technique. The specifications are shown in Figure 6.

Explosive Classification	1.4 G
UN Serial Number	0431
ESTC Classification	T1950
NEC/NEQ	157 grammes
Temperature	Approximately 250°C
Burn Time	Approximately 4 minutes

Figure 6 - Low Temperature Thermite Specifications

The advantage of the Low Temperature Thermite over the more common High Temperature Incendiary devices, is that there is a much reduced chance of a high order detonation being induced. The burning temperature of the LTT is approximately 250°C which is below the detonation temperature of many military explosives. A wide variety of explosive types have been routinely destroyed using LTT over the last 18 months, with no high order events being induced by the LTT.

EXPLOSIVES
TORPEX
TORPEX 2 (HEXAMIN)
TETRYL
TNT
RDX
RDX 60/WAX 40
PETN
HEXOLITE
ISOLANE

Figure 7 - Explosive Types Regularly Destroyed by LTT

LTT is a safe and efficient alternative to Open Detonation in many instances, and when combined with the 'MARLIN' Hydro Abrasive Cutting System, it provides the capability to conduct a complete render safe procedure on the majority of UXOs in virtually any operational scenario.

CONCLUSIONS

There is little doubt that the future of Hydro Abrasive Cutting for the demilitarisation of ammunition and explosives is looking bright, with the development of the AVOCET system. The ability to safely cut explosives with such "low pressure" systems has now been clearly demonstrated. Research is continuing at pace in order to provide the "safe" operating envelopes of the "higher pressure" DIAJET® systems, and there is no reason to suppose that the future of these systems will not become equally as bright.

'MARLIN' has also proved to have been a technical success, and has already attracted serious interest in the use of such portable systems for use on EOD operations, as swell as the other more commercial applications. The technology is continually developed as different users have different requirements for their manipulation systems.

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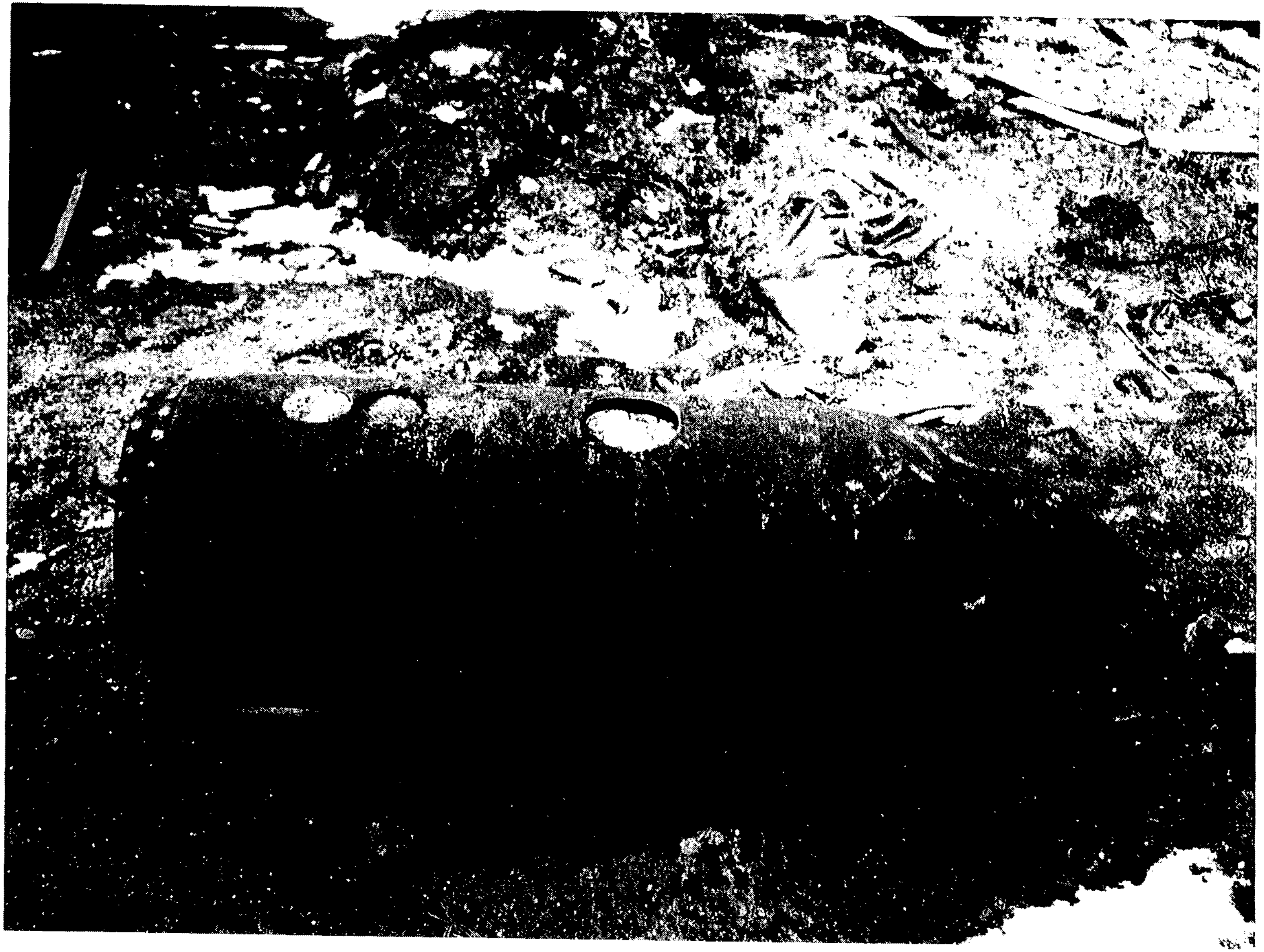
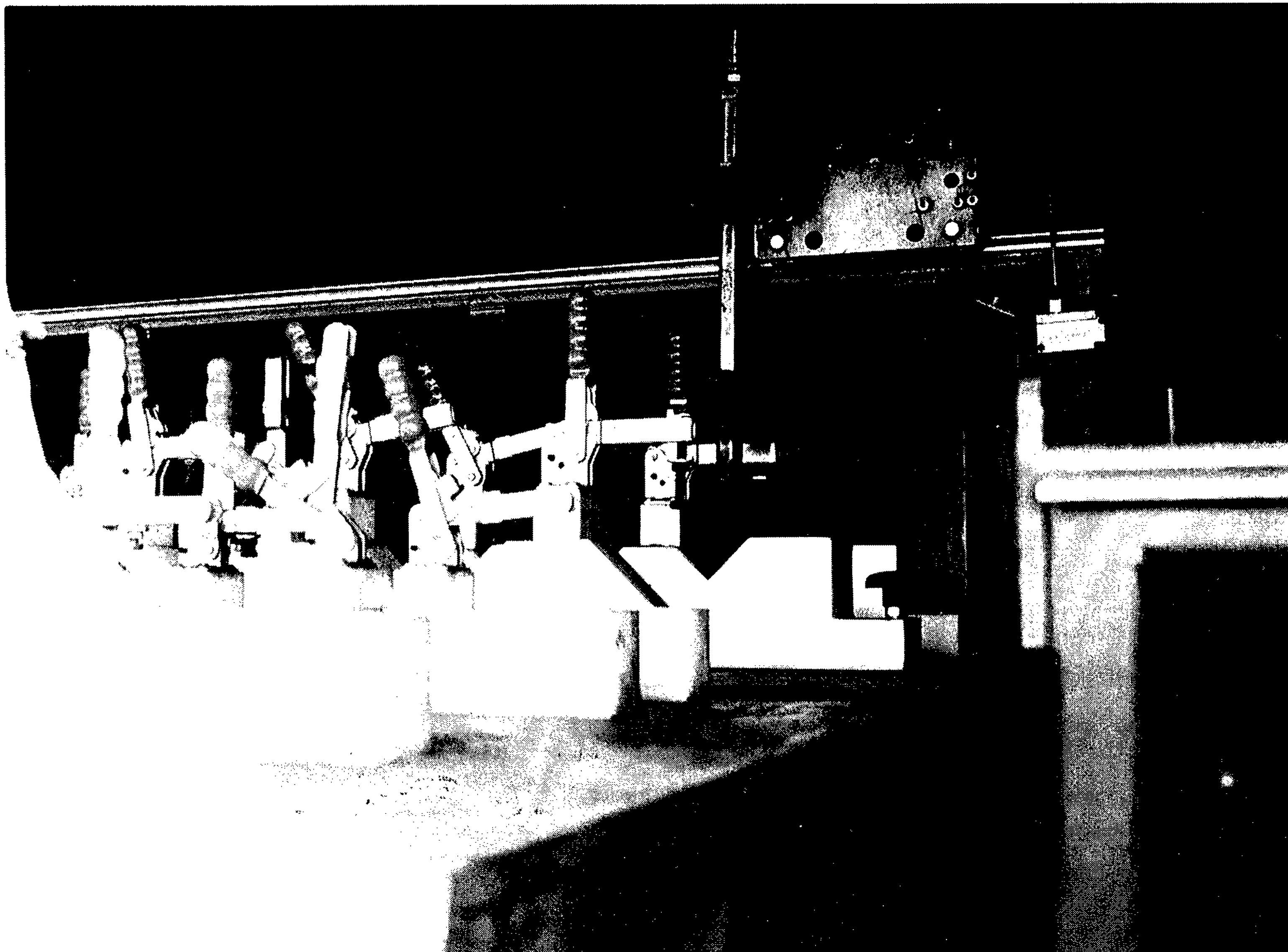
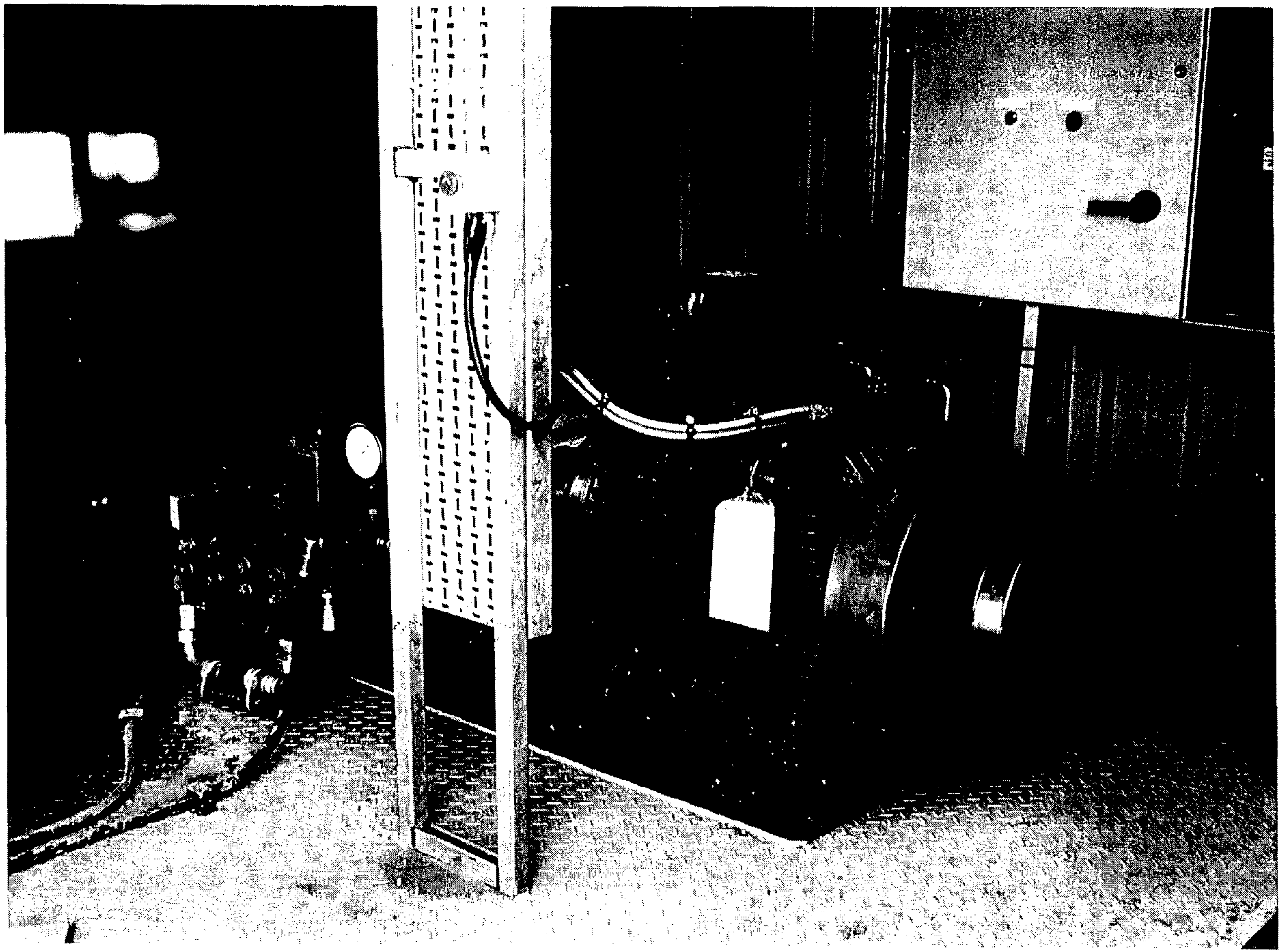


Photograph No. 1: Old Training Munitions Awaiting Disposal at DTEO Shoeburyness



Photograph No. 2: AVOCET HAC System - Manipulation and Cutting Head Module



Photograph No. 3: AVOCET HAC System - Pump and Pressure Cylinder Module

Photograph No. 4: Prototype MARLIN During Initial Trials - September 1995

MUNITION ASSESSMENT AND PROCESSING SYSTEM (MAPS)

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ABSTRACT

Ongoing and future efforts under the Aberdeen Proving Ground (APG) Installation Restoration Program are expected to include the accidental and intentional recovery of chemical munitions. The procedure for handling chemical munitions recovered at APG entails the transfer of agent fill to separate containers and neutralization in the existing Resource Conservation and Recovery Act (RCRA) permitted Chemical Transfer Facility (CTF). Currently the CTF is capable of assessing and draining only non-explosively configured munitions. The CTF does not allow for assessing and processing of explosively configured munitions. The Munition Assessment and Processing System (MAPS) is being designed, developed, and acquired to provide the capability to process explosively configured chemical munitions. It is the purpose of this paper to describe MAPS as it is presently being designed to include physical and functional requirements.

BACKGROUND

The Defense Environmental Restoration Program (DERP) was established in 1984 to promote and coordinate efforts for the evaluation and cleanup of contamination at Department of Defense (DoD) installations. This program includes:

- The Installation Restoration Program (IRP), where potential contamination at DoD installations and formerly used properties is investigated and, as necessary, site cleanups are conducted.
- Other Hazardous Waste (OHW) Operations, through which research, development and demonstration programs aimed at improving remediation technology and reducing DoD waste generation rates are conducted.

The initial stage of the IRP is to conduct an installation-wide study to determine if sites are present that may pose hazards to public health or the environment. This study is called a Preliminary Assessment (PA) and contains available information on the source, nature, extent, and magnitude of actual and potential hazardous substance release at sites on the installation. A Site Inspection (SI), consisting of sampling and analysis, is conducted to determine the existence of actual site contamination. Information gathered is used to evaluate the site and determine the response action needed. Contaminated sites are investigated fully in the Remedial Investigation/Feasibility Study (RI/FS). The focus of the RI is to determine the risk to the general population posed by the contamination, while the focus of the FS is to evaluate remedial action alternatives for the site. After Interagency Agreements (IAGs) are reached with the appropriate EPA and/or state regulatory authorities on how to clean up the site, Remedial Design/ Remedial Action (RD/RA) work begins. The IAG for the Edgewood Area at Aberdeen Proving Ground, MD was finalized in 1990. (Defense Environmental Restoration Program, Annual Report to Congress for Fiscal Year 1992, April 1993).

The Chemical Stockpile Disposal Program (CSDP) was established in 1986 in accordance with Public Law 99-145 to destroy the United States stockpile of lethal unitary chemical agents and munitions. In 1991 Congress, having noted that the CSDP did not include additional chemical warfare related materiel requiring demilitarization, directed the Department of Defense to establish what is now known as the Program Manager, Chemical Demilitarization (PMCD). The mission of PMCD is to execute chemical materiel destruction of the United States stockpile of chemical warfare agents and munitions and all non-stockpile chemical materiel (NSCM). (U.S. Army Program Manager for Chemical Demilitarization, Non-Stockpile Chemical Materiel Program Implementation Plan, August 1995).

In Section 176 of Public Law 102-484, the 1993 Defense Authorization Act, Congress directed the

U.S. Army to submit a report that identifies the locations, types, and quantities of non-stockpile chemical materiel (NSCM); explains the methods to be used for their destruction: provides the estimated cost and schedule for their destruction; and, discusses transportation alternatives. At Army installations all activities concerning handling and destruction of chemical warfare materiel (CWM) are coordinated with and authorized by PMCD. The installation commander has the overall responsibility for activities at potential burial sites. Support is rendered by PMCD, the U.S. Army Corps of Engineers (USACE) and the Army Environmental Center (AEC).

Based upon an analysis of the Chemical Weapons Burial Historical Survey Report, four separate types of CWM burial sites were established -- these being Chemical Agent Identification Sets (CAIS) Sites, Small Quantity Without Explosives, Small Quantity With Explosives, and Large Quantity. The Edgewood Area at Aberdeen Proving Ground is designated as a Large Quantity Chemical Warfare Materiel Site. Such a designation suggests that a substantial development and cleanup effort involving a range of remediation approaches and technologies is required for the Edgewood Area. The Army expects to rely heavily on CSDP experience and from the remediation of small burial sites in formulating plans and developing systems to deal with these sites. (Non-Stockpile Chemical Materiel Program, Survey and Analysis Report, Program Manager for Non-Stockpile Chemical Materiel, November 1993).

At APG, the intended treatment procedure for recovered chemical munitions entails the transfer of the agent fill to separate containers, and then neutralization of the agent in the existing Chemical Transfer Facility (CTF). Currently, the existing Chemical Agent Transfer System (CHATS), located within the CTF, is capable of assessing and draining non-explosively configured munitions. The CHATS configuration and location does not allow for the processing of explosively configured munitions. A capability for the drilling, draining and decontamination of explosively configured munitions is required. The Edgewood Research, Development, and Engineering Center (ERDEC) was requested by the U.S. Army Garrison, Aberdeen Proving Ground, Directorate of Safety, Health and Environment (DSHE) to assume the lead project management role in the development and acquisition of this capability.

It is against this background that an effort was initiated to combine both agent and explosive containment functions into a fixed system. The effort is a cooperative effort involving PMCD, PMNSCM, APG, and ERDEC. It is being conducted with an eye towards cost reduction, and is called the Munitions Assessment and Processing System (MAPS). It is MAPS which is the subject of this paper and which is described in more detail below.

THE SYSTEM

General

MAPS is designed to provide analysis, assessment, and processing of explosively configured chemical munitions. The basic design for MAPS is derived from an analysis of operational requirements to both assess and process the munitions and agents as shown in Table 1. However, in view of the long-standing research, development, test, and evaluation activity at the Edgewood Area, it is reasonable to expect that some munitions may well contain other known and unknown chemicals. It is against these possibilities that the operations process, as shown in Figure 1, was developed for MAPS.

A more detailed design for MAPS is being developed and is based upon analysis of those technical performance requirements necessary to support efficient and effective operations while ensuring the safe containment of potential agents and explosions. A roll-up of performance requirements suggests a system which should consist of both Process and Control Facilities on a supporting site. A possible layout of the MAPS Site is shown in Figure 2.

MAPS will be operated during normal duty hours and will be capable of year-round operations. It will process only one munition at a time, but the number of munitions to be processed during a given period of operations will be dependent upon the types and conditions of the munitions being processed. In any

Table 1: Munitions and Potential Fills to be Assessed and Processed by MAPS

Chemical Agent	155 mm	105 mm	75 mm	Livens	4.2 inch	4 inch Stokes
AK-Hydrocyanic Acid & Ethyliodoacetate						X
BA-Bromoacetone			X			
CA-Bromobenzylcyanide			X			
CG-Phosgene			X	X	X	X
CK-Cyanogen Chloride				X	X	
CL-Chlorine				X		
CNB-Chloroacetophenone + Benzene					X	
CNS-Chloroacetophenone + Chloroform					X	
FM-Titanium Tetrachloride (Smoke)			X	X		
FS-Smoke (Sulfur Trioxide)					X	
GA-Tabun (20% Chlorobenzol)					X	
GB-Sarin	X	X				
H-Mustard	X				X	
HD-Distilled Mustard	X	X		X	X	
HS-Sulfur Mustard (15% C. Tetrachloride)			X			
HT-60% Mustard, 40% Vessicant					X	
KSK-Ethyliodoacetate and Ethanol						X
L-Lewisite					X	
Magnesium Arsenide				X		
NC-80% PS and 20% Stannic Chloride			X	X		X
PG-50% PS and 50% CG						X
PS-Chloropicrin				X		X
PWP-Plasticized White Phosphorus					X	
Surpalite-Diphosgene				X		
TH-Thermite						X
VX- Nerve Agent	X					
WP-White Phosphorus			X		X	X

event, MAPS will be capable of being operated by personnel wearing personnel protective equipment (PPE), and will have the facilities to allow for personnel decontamination and the donning and doffing of PPE.

Simplicity of design will be maximized to provide a system that will use state of the art technology and off the shelf material/equipment. MAPS will have all manual operations except for the remote control of drilling operations which will be designed so as to minimize the risk of accidental detonation.

Process Facility

The Process Facility will consist of an entry/airlock, an assessment and process area, a PPE decon and don/doff area, an X-Ray/PINS room, an air monitoring room, an equipment storage room and a storage tank area. A layout of the Process Facility is shown in Figure 3. The facility will contain both munitions assessment and processing equipment. Assessment equipment will include a real-time X-Ray system, PINS and a chiller/heater system. Processing equipment will include all equipment necessary for munitions unpack, drill, drain, decontamination, and repack. The facility will also provide equipment so as to support the transport, handling, and temporary storage of munitions, decontaminants, chemical agents and chemical waste. The heart of the Process Facility is the Process Area which contains the Process Box, the Drill Box and the Explosion Containment Chamber. Each of these items are discusssed in more detail below. A layout of the Process Area is shown in Figure 4.

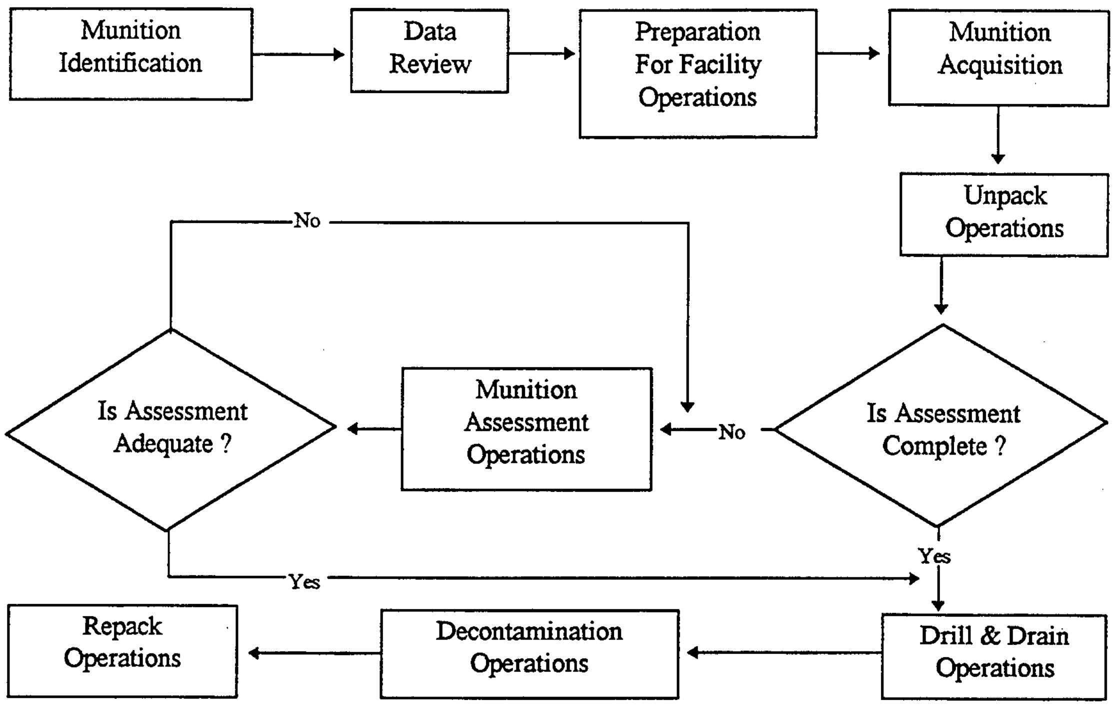

Figure 1: MAPS Operations Process

Process Box

The Process Box will be a multifunctional glove box which allows for the handling of toxic/hazardous chemicals and contaminated associated with the explosive munitions, while providing for vapor containment and a level of isolation and safety for personnel. The Box will provide for munitions unpacking, X-Ray assessments, chemical fill collection and bottling, decontamination, and material repackaging.

The Process Box will be configured into two separate sections to allow sequential munition processing operations while limiting the spread of contaminants. One section will allow for packing/unpacking and removal of overpacks, and the other section for decanting of the munition and X-ray compatibility. Each section will provide windows for operator viewing, and glove ports of oval shape for maximizing reach from either side of the Box. The Box will access facility ventilation located overhead, and drain all neutralized liquid chemicals from outlets at the bottom of the process box to dedicated facility drains.

Drill Box

The Drill Box will provide a means for remotely drilling munitions within the Explosion Containment Chamber (ECC), and then supporting the transfer of agent contents. The Drill Box will be a transferable unit that moves back and forth from within the ECC to an interface with the Process Box. When connected with the Process Box, munitions are moved in and out of the Drill Box. It will be capable of drilling two 0.5 inch holes into the munition. The Box will be equipped with two drill systems. The vertical and horizontal positioning of the drill systems will be mechanically controlled to within an 0.20 inch.

Although the actual drill operations will be remotely controlled all operational equipment will have mechanical stops incorporated into the design. The Box will be under continuous ventilation when drilling is not occurring. The ventilation system will be able to close in the event of an explosion. The drill towers will be mechanically fixed in the length dimension. Drilling activity will be monitored through close circuit audio /video. The drill towers will be able to remotely vary the left and right position. Left and right positioning will be

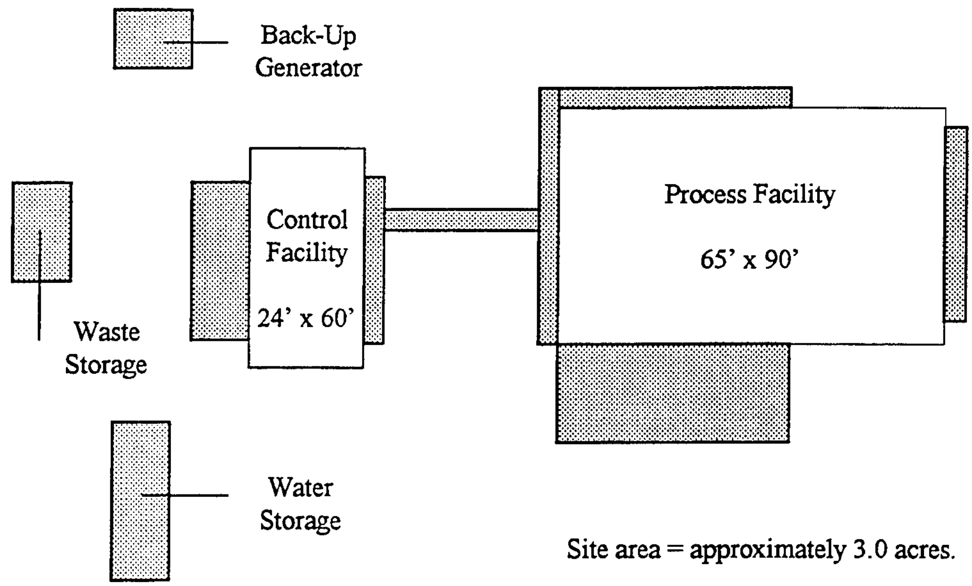

Figure 2: MAPS Site Layout (not to scale).

accomplished via a screw drive and the drills will function independently.

Drill Box Transfer System

The Drill Box Transfer System will be used to support the movement of the Drill Box between the ECC and the Process Box. It will consist of a ECC Support Cart, a Process Area Support Table, two rails connecting the ECC Support Cart to the Process Area Support Table, and two rails connecting the Process Area Support Table to the Process Box.

All operations involving the drill box will be capable of being done safely with a maximum of two technicians wearing full PPE. All components will be capable of being locked/pinned together to prevent separation during movement of the Box.

Explosion Containment Chamber

The chamber is in essence two concentric steel cylinders with a glycol-water mixture between the two cylinders. There are two doors at only one end of the chamber with the outside door being a sliding door while the inside door opens toward the inside. The outside dimensions of the chamber are approximately 264 inches in length by 95 inches in diameter. Inside dimensions are approximately 169 inches in length by 89 inches in diameter. The weight of the ECC, without the Drill Box and related fixtures, is approximately 57,000 lbs. The chamber will contain the explosive forces of 13 lbs. of TNT.

The ECC will be fixtured to facilitate Drill Box operations. This includes lighting, audio/video cameras, grating, electrical power, fire suppression, air monitoring, ventilation, pneumatic air supply to the drill motors, and remote drill control lines.

X-Ray System

The X-Ray system will be a stand alone system operating primarily from outside the Process Box so as to acquire real-time images of munitions positioned within the Box. The system will also be transportable so as to permit imaging of munitions in overpacks while they are positioned in the process room outside the Box. In both cases, the system will simultaneously display images both at the operational control position within the Process Facility and at the operations room within the Control Facility. The system will also be capable of

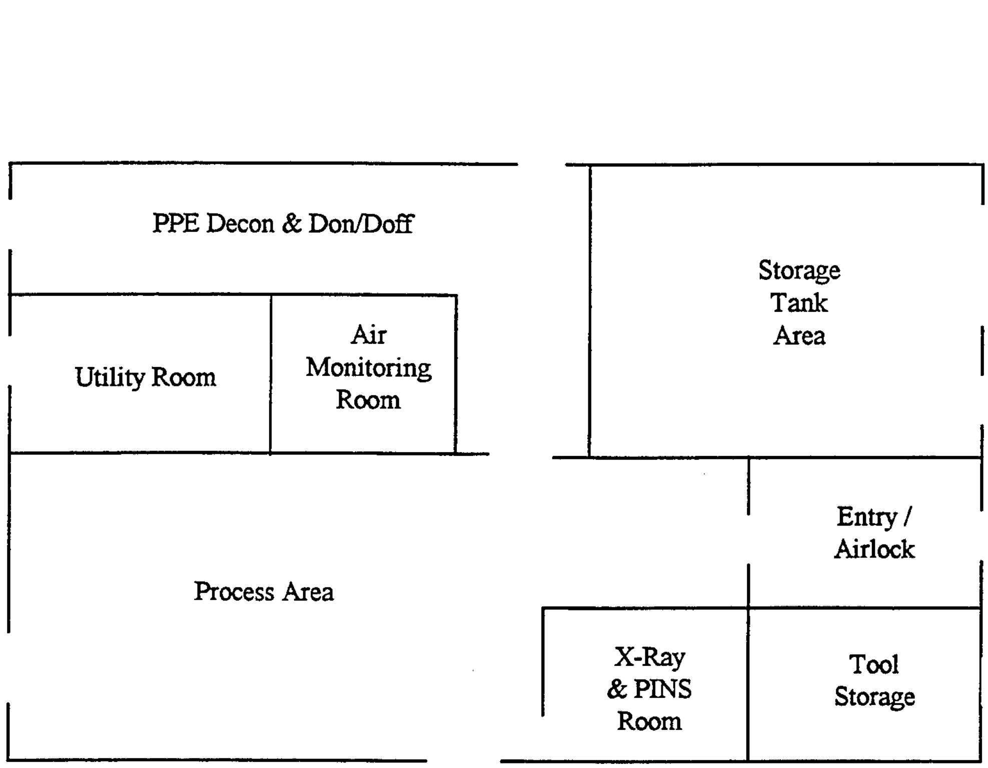

Figure 3: Process Facility Layout (not to scale).

image enhancement, and will store all images in digital format. The system will be capable of imaging munitions from at least two orthogonal positions while resolving all internal dimensions to the level of 0.10 inches.

Radiaton shields will be provided in both the process room and the X-Ray/PINS storage room. The shield within the process room will be transportable while the shield in the storage room will be wall-fixed.

The system will be designed to automatically shutdown when radiation levels in excess of 2 milliroentgens per hour are detected. It will also include the necessary detection equipment to determine radiation leakage in excess of NRC guidelines.

Chiller / Heater System

The Chiller / Heater System will be a stand alone system capable of chilling and heating munitions. It will consist of a chiller/heater unit and a munition holding fixture.

The system will be capable of reducing the fill temperature of each munition in gradations of 20°C, to -10°C and -38°C. The cooling rate will be such that the fill temperature may be lowered from -10°C to -38°C within a period of 2 hours. The munition holding fixture will firmly hold the munitions at a 45° angle from the vertical while the munition fill temperature is lowered.

HVAC/Filtration

An integrated HVAC/filtration system will permit safe and efficient year-round operations. There will be gradated reductions in air pressure as the air flows from the areas of lower probability of agent vapor to the areas of higher probability of agent vapor. The vapors of all agents to be assessed and processed within the Process Facility will be safely filtered and monitored. Conditioned, filtered supply air will be delivered to the Process Building by a constant volume, horizontal draw-through, DX cooling, electric heating, and outdoor air handling unit located under a canopy.

Air Monitoring

The air monitoring system will consist of two near-real time (NRT) monitors and one gas chromatograph with mass selective detector. (GC/MSD). NRT-1 will sequentially monitor ambient air from 10 different locations within the process facility. NRT-2 will be dedicated to on-demand analysis of process vapor samples from five different locations having the highest probability of vapor release. General ambient air conditions will

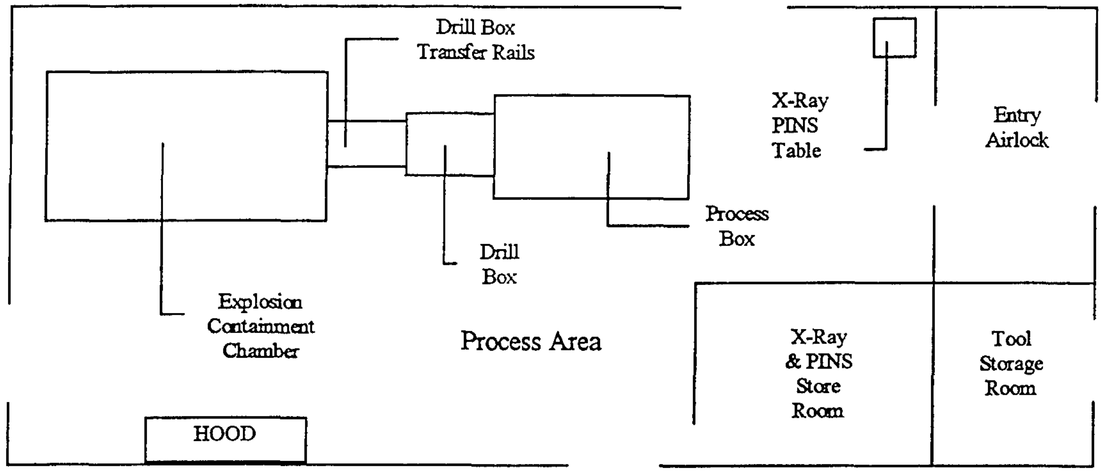

Figure 4: Process Area Layout (not to scale).

be monitored to ensure that conditions in the entry air lock, the processing area, and the air monitoring room are maintained below 0.8 TWA. The GC/MSD system will provide a general capability to identify and monitor the concentration of a relatively broad variety of unknown vapor samples.

The sampling system will be comprised of automatic and manual valves and manifolds located in the air monitoring room. The sampling system will convey the sample from the appropriate heated sample lines to the NRT monitors and GC/MSD system. Heat-traced teflon sampling lines will convey sample from each sampling location to the stream selector for each NRT monitor. Sample lines will be insulated and heated along the entire length to minimize condensation or absorption of compounds on surfaces. To avoid the possibility of interference, or contamination such as from the use of a silver fluoride pad, three separate sample lines will be provided between each monitored location and the air monitoring room.

The two NRT monitors will consist of interchangeable analytical modules as required to simultaneously monitor all the chemicals in the blister agent group, the nerve agent group or the industrial chemical group. Lewisite will be chemically converted to a compound which is stable and can be detected by a halogen-selective detector (XSD).

A data acquisition and control system will provide a means to operate, monitor and service the NRT monitors from a local terminal. The system will include a host computer and software and will be located and operated in close proximity to the NRT monitor. A data communications network will provide a means of inter-connecting all NRT monitors for the purpose of archiving historical data and reporting on system status. The system will include a host computer, short-range modem and software located at and operated from the Control Facility. The system will also send audible and visual alarms to status panels located in both the Control and Process facilities.

Communications

MAPS will have a communications system that permits communications among all areas and during all phases of the assessment and processing operations. There will be an emergency alarm capability which permits the notification of emergency situations to include air monitoring and sampling, ventilation flow and pressures, filtration, backup power, fire, and severe weather. All personnel will be alerted with regard to X-Ray and Portable Isotopic Neutron Spectroscopy (PINS) assessment operations. There will also be a closed circuit video system that permits the observation, analysis, and control of key assessment and processing operations as well as general observation of site facilities and grounds.

Control Facility

The Control Facility will provide for the overall control of processing operations and the technical analysis of munitions to be assessed and processed. It will store and support the use of information and data which describes the munitions to be assessed and processed. During hazardous operations, the Control Facility will also provide for the general support of personnel normally assigned to the site.

The operations room is the center for controlling and monitoring all MAPS operations. There will be a central console equipped for all normal communications and having alarm indicators from other stations; a control station for remote drill operations; and, other stations which may not be manned full time. Such stations will monitor the status of HVAC/Filtration, back-up power and air monitoring.

CONCLUSION

Once operational, MAPS will focus in the near term upon the assessment and processing of explosive chemical munitions presently in storage at the Edgewood Area. However, it is envisioned that MAPS could very well serve as an RDT&E facility in support of ERDEC, APG, PMCD, and PMNSCM. Such support might include technology demonstrations and non-destruct tests and evaluations. MAPS is expected to be a cost effective addition to the list of tools and systems available in support of the U.S. Army Chemical Demilitarization and Remediation Program. Ultimately, MAPS may serve as a model for other installations.

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THE TECHNOLOGY AND METHODOLOGY FOR EOD SITE ASSESSMENT

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ABSTRACT

The clean-up of formerly used defence sites presents an expensive and enormous task. Traditionally, such clean-up work has been let as a schedule of rates contract in which the contractor shares none of the cost risk and operates under a disincentive to improve work efficiency. The development of an efficient procedure for determining the concentration and total number of items that must be disposed of, will permit remediation to be contracted on a fixed cost basis. Not only does this provide the contracting party with the ability to properly budget the expenditure of available funds, but it provides the incentive for the successful contractor to increase their profit margin through improved work efficiency.

With the advent of digital, recording magnetometer instrumentation with in-built positioning and detailed knowledge of the magnetic properties of different UXO types, it is practical to sample the magnetic field along regularly spaced transects and through analysis of the data so recorded, determine the distribution of contamination and the total number of ferrous items to be treated as potential UXO. Data obtained, allows the achievable detection depth to be quantified for quality assurance purposes. In addition, areas identified as free or only lightly contaminated can then be cleared first and the cash-flow generated from the early release of this land used to fund the remaining operation.

Data presented as a case example demonstrates that a 10% statistical sample performed in the manner proposed can yield a total contamination estimate that is within 2% of the true figure. Given the potential savings achievable through fixed cost tendering, fast-tracking of cash-flow from land recoveries, and from having access to accurate budgeting detail, expenditure of the order of $100 per Ha for acquiring this information is the most responsible decision available.

INTRODUCTION

The Problem

The 20th century has seen an unprecedented use of military ordnance for training purposes and many billions of items have been involved world wide. With failure rates of up to 20% for some explosive devices, severe hazardous contamination has resulted. In some countries, as much as 2.5% of the total land area has been contaminated by such military training activity. Remediation of this land presents an enormous task. Achieving this with available budgets will require acceptance of new and innovative solutions to the way EOD is performed.

Traditionally, EOD has been let as a schedule of rates contract because neither the contracting party nor the contractor has been able to accurately predict the amount of work required. It is the nature of such contracts that all of the financial risk is born by the contracting party while there is a real disincentive for the contactor to improve work efficiency.

Many of the formerly used US defence sites cover several hundred square km. Within this area the contamination levels are known to vary from zero to several thousand items per hectare. Responsible management of EOD spending at these sites cannot be achieved without detailed information exceeding that available from historical records, quantifying the distribution and nature of contaminants.

The Solution

The solution available is an efficient and statistically sound method for quantifying the distribution and type of contaminants over the whole area of concern. This information may be presented as a contour map of the number of items per Ha. The solution also provides essential geological information from which a contour map may be prepared defining the depth to which a given type of ordnance can be detected with any nominated probability appropriate to the intended land use.

For several years now the Geophysical Research Institute (GRI) has been performing the fundamental research required to develop a technology and methodology that would enable the Australian Department of Defence to measure the ferrous contamination at some of its former and current defence sites. Since 1990 GRI has provided this service to the Australian Army at sites including a former

artillery proofing range, a demolition range that was to be redeveloped as a weapons storage facility and at the site of the Sydney 2000 Olympic stadium. The technology is also being used by the Australian Air Force at its current bombing ranges. In 1994 the technique was successfully trialed at a former East German military range being considered for development into a new airport for Berlin.

The first North American site to undergo assessment using the method was the 180 square km range at Tracadie, in New Brunswick, Canada. This landmark contract was let in 1995 by the Canadian Department of National Defence to ADI-Dillon using the technology and services of GRI.

OBJECTIVES OF SITE ASSESSMENT

The objectives of site assessment are to:

- measure the number of items of unexploded ordnance (UXO), or items that must be treated as potential UXO using a statistical sampling procedure. This procedure accommodates the localised nature of some occurrences.
- determine the depth at which the detected items occur.
- document the distribution of the different types of UXO encountered in the area of concern.
- define each of the above with sufficient precision to enable an accurate costing to be made for the remediation of the area to a predefined standard.
- determine the optimum search specification parameters for the geological conditions and ordnance types present.
- determine the depth to which a nominated detection assurance may be achieved for the particular items encountered.
- minimise in the assessment task, the expensive and time consuming requirement to confirm detection by excavation.

With accurate knowledge of this important information it then becomes possible to:

- accurately budget for remediation.
- make sensible decisions as to the appropriate land use, knowing the cost of the relevant level of remediation.
- prioritise remediation spending, both between sites and within sites, on the basis of cost per unit area, land value and proposed future land use.
- generate cash-flow from the early release of clean or readily cleared areas within a range and by so-doing, fund the remaining remedial operation.
- pass on the cost risks to the contractor.
- apply pressure upon contractors to address means of increasing the efficiency of their operation.
- achieve cost-saving through fixed price contracts, minimised debt levels and properly managed budgets.

SITE ASSESSMENT TECHNOLOGY

Site assessment technology that avoids or minimises the expensive and time consuming requirement to confirm detection by excavation is reliant upon the same fundamental principles that permit detection assurance to be quantified.

In the case of ferrous ordnance, the factors affecting detection involve the sixteen major variables listed in Table 1. Some of these are associated with the magnetic properties of the object and the environment where it is located. Other variables are assigned to the data acquisition parameters.

Search effectiveness is specified in terms of the UXO type and the depth to which that type can be detected with a nominated level of certainty (Stanley, 1994). In order to quantify such a certainty, detailed knowledge is required about the variability of the magnetic properties of each ordnance type, both between individual items and with orientation of the items in the ground. Also required is measurement of the magnetic interference present from geological or cultural sources in the proximity of the search. An item of UXO may only be detected if its magnetic field exceeds the interference amplitude over the sweep width of the detector.

Ferrous UXO will exhibit magnetism, which is the sum of a remanent component acquired during manufacture and an induced component which is related to the magnetic susceptibility of the iron composition and the geometry and orientation of the item. Figure 1 contains a histogram of magnetic anomaly amplitudes at 400 mm elevation, for a sample of 312 measurements performed involving hand-grenades at different orientations. A comprehensive database of such properties is essential to quality assurance (QA) specification. The depth to which assurance can be given is dependent upon the worst case signal amplitude, the amplitude of the magnetic interference, the elevation above ground at which the detector is operated, and the interval between magnetic measurement data.

For a given magnetic detector type, data acquisition specification and magnetic interference, the detection depth may be described by means of a graph of UXO magnetic properties as a function of their depth below the detector. Figure 2 contains an example of such a graph.

These same principles which permit detection QA to be

quantified may be applied conversely to specify the detection diameter for a particular UXO type as a function of its depth below ground and the elevation of the detector above ground.

Of the currently available magnetometer systems, that most suitable for UXO site assessment is the Geophysical Technology model TM-4. The TM-4 is based upon the total field, optically pumped magnetic sensor which provides sensitivity and measurement rates appropriate to the task. The TM-4 may be hand-held, and because it incorporates in-built positioning that can be used in any environment, it is able to collect positioned data while continuously travelling regardless of speed. At the Tracadie range in New Brunswick, quality data was acquired in forests that were nearly impenetrable on foot, and at times during most unfavourable weather conditions.

SITE ASSESSMENT METHODOLOGY

Stage 1 - Historical Review

The first phase of any site assessment should be the search of historical records as these provide a baseline for the geophysical investigation. Analysis of geological information may enable the expectations of search effectiveness and associated data analysis problems to be anticipated.

Stage 2 - Reconnaissance

A digital, total field magnetometer such as the TM-4 should be operated with its sensor at a known elevation above ground, recording data at regular sample intervals no greater than 25% of the sensor elevation. Data should be acquired along regularly spaced, parallel transects that are typically 50 m apart. To achieve this in heavily forested areas such as Tracadie, pre-marked control lines were surveyed in place at 500 m intervals perpendicular to the magnetic survey direction.

The reconnaissance transect separation of 50 m will permit the magnetic noise envelope to be measured over the whole site.

Using the measured noise envelope, the UXO magnetic properties database and the known sensor elevation, the effective search width of the total field sensor may be predicted for any ordnance item of interest. Usually this will be calculated for the worst case situation involving the smallest item anticipated. With a noise envelope of 1 nT and a sensor elevation of 1 m, the reconnaissance specification will permit items down to hand-grenade size to be detected over an effective search diameter of 1.2 m providing a 2.4 % sample of the area traversed. For larger items, the predicted search diameter will be increased.

It should be noted that nowhere in the area surveyed is farther than nominally 25 m from real data ensuring that no target impact area will escape detection.

The line data recorded is then processed. Analysis of a running data window derives the magnetic noise envelope. A pattern recognition algorithm then detects dipole and monopole sources that exceed the noise envelope. Counting such occurrences per unit transect length and dividing by the appropriate search diameter calibration factor provides a measure of ferrous items per unit area.

The detection algorithm also computes the depth to each target detected.

The line data is inspected for signature changes. These may be associated with changes in local geology, changes in the population of ferrous sources or a combination of both. Figure 3 contains two magnetic profiles 250 m long. Profile "A" displays a low amplitude, "noise only" signature while profile "B" contains noise plus a pattern of dipolar features characteristic of UXO contamination.

Each signature type will be characterised by the conduct of a "calibration" survey. This is achieved by mapping a small area of typically 0.25 Ha with a survey designed to detect all items present. All items detected will be excavated and documented as for a clearance operation.

The conduct of a calibration survey will derive the following information:

- characterisation of the distribution of ordnance types.
- the ratio of live to inert targets will be determined.
- the predicted calibration factor (converting line data to items per Ha) will be refined relevant to the actual distribution of ordnance present and the depth at which they occur.
- some signatures will be confirmed as having purely a geological or non-military source (eg., a laterite horizon or the site of a farm settlement pre-dating the military range).

This information is valuable for the following reasons:

- it permits the encountered distribution of target types to be extrapolated over areas sharing the common signature.
- it permits single purpose targets to be identified from

multiple purpose targets where, for example, the remediation cost may be severely increased by the need to recover every piece of bomb fragmentation in order to identify each grenade or small bore projectile.

- it increases the accuracy with which the number of items per Ha, live and inert, can be determined.
- signatures confirmed to be associated with contamination-free areas may be identified for immediate release.

Stage 3 - Selected Detailed In-fill

Those areas confirmed from the Stage 2 reconnaissance as target areas, areas where more severe contamination was encountered or areas where demolition and waste burial are suspected, should be subjected to in-fill mapping. This may be achieved using the same position control lines as for the reconnaissance survey and by reducing the transect line spacing to, say, 10 m. The percentage sample then used in the calculation of contamination statistics is increased to at least 12%. The farthest distance from any place within the in-filled area to real data is reduced to 5 m providing a high degree of credibility to data interpolated between survey lines. With such a line spacing, the probability of missing a significant burial pit is manageable.

Processing the data from the in-filled survey area replicates that performed on the reconnaissance data and refines the result in accuracy and spatial resolution.

SITE ASSESSMENT DELIVERABLES

Site assessment performed in the manner described generates the following deliverables necessary for formulating decisions relating to clearance priorities and sensible future land use. It provides the information necessary to design a work plan that maximises self-funding through the cash-flow generated by early release of the most readily decontaminated land and it provides EOD contractors with the information necessary to prepare a fixed cost quotation for their work.

There are five major data sets that may be derived:

- a contour map of the number of ferrous items per Ha. This is the primary information relating to the cost of clearance.
- a contour map showing expected numbers of items per Ha by UXO type. This information would enable the contractor to resource the clearance operation with appropriate excavation and disposal technology.
- a contour map of the magnetic noise envelope. This data can be used to design the optimal search parameters specification and it provides the data from which the clearance depth to a nominated assurance probability can be determined for any UXO item.
- a contour map showing the depth to which particular items of UXO encountered on the site can be detected with a specific assurance probability.
- a contour map showing the average depth at which detected items occur.

AN EXAMPLE

A formerly used defence area of approximately 25 Ha and containing an artillery target has been investigated.

Figure 4 contains a contour map of the ferrous items per Ha determined from a "reconnaissance" specification site assessment survey in which data were recorded with a TM-4 magnetometer at 0.8 m sensor elevation, 0.2 m sample interval and 50 m line spacing. Contamination ranging from less than 50 items per Ha to just over 400 items per Ha near the target centre was mapped. The total number of items of contamination determined from this 2% sample was 5,650.

Figure 5 contains a contour map of ferrous contamination determined from a "detailed" survey specification, in-filled to 10 m line spacing. Resolution of the contaminated areas has now been improved. The total number of items of contamination determined from this 10% sample was 4,950.

Figure 6 contains a contour map of the "true" ferrous contamination determined from a survey, in-filled to 1 m line spacing. The total number of items of contamination determined from this 100% sample was 4,809.

From this data, the 2% statistical sample can be seen to have been accurate to within 17% and the 10% sample accurate to within 2% of the true contamination figure.

Figure 7 contains an example of a contour map of noise amplitude expressed in nT. When used in conjunction with the data-base from which Figure 2 was graphed, the noise envelope data may be used to prepare a contour map showing the depth to which a particular UXO type may be detected with a nominated level of certainty.

Figure 8 shows the contour map of the depth to which a 105 mm HE projectile may be detected with "100% confidence" where, in this case, 100% is defined as an "insurable" risk of nominally less than 1 in 100,000.

THE COST ADVANTAGE

The site assessment technology and methodology described has provided a cost-effective solution to the problems associated with determining the extent and type of contamination on large military ranges.

While actual costs vary considerably with local conditions, a 100 sq km site in open country with an average contamination density of 100 items per Ha might cost of between \$50m and \$100m to clear. Using the conventional methodology involving a 10% sample clearance, the site assessment would then cost between \$5m and \$10m. Its results would not provide sufficient detail to permit fixed cost tendering, to allow "clean" areas to be defined for early release or to define the clearance assurance standard that is achievable given the local geological conditions. The assessment methodology proposed would acquire all of this information for a cost of around \$1 million.

REFERENCE

Stanley, John M. 1994. "Achieving 100% quality assurance in ferrous explosive ordnance disposal." *Proc. UXO and Range Remediation Conference,* Boulder, Colorado. May, Pages 51 - 59.

FACTORS AFFECTING UXO DETECTION

MAGNETIC PROPERTIES

- UXO type and mass
- Orientation of UXO in the ground
- Depth of UXO below ground surface
- Time UXO has been in the ground
- Composition and manufacture of individual items
- Magnetic properties of the soil where UXO buried
- Magnetic interference from temporal sources
- Magnetic latitude of the search site

SEARCH PARAMETERS

- Magnetometer type - total field or gradiometer
- Magnetometer sensitivity
- Elevation of the sensor above the ground
- Sample interval along the search line
- Search line spacing
- Tolerance allowed in sensor elevation
- Tolerance allowed in search line spacing
- Whether a base-station magnetometer is used

TABLE 1 The sixteen major variables affecting the detection of ferrous ordnance.

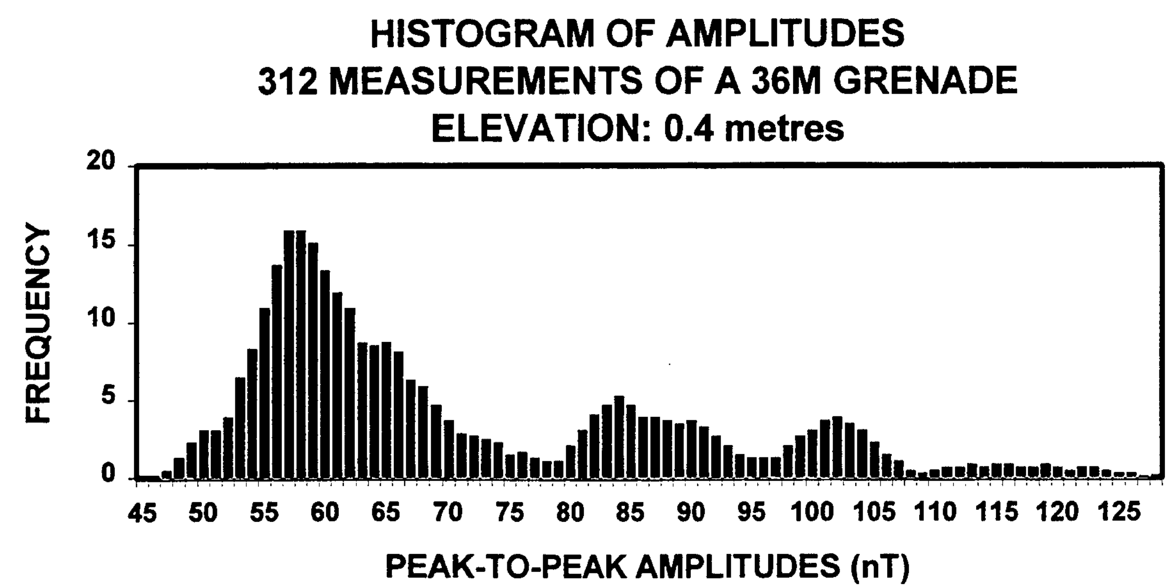

FIGURE 1 A histogram of magnetic anomaly amplitudes at 400 mm elevation, for a sample of 312 measurements performed involving hand-grenades at different orientations. The magnetic signature of a UXO type determines both its detection depth and the effective search width of a magnetic detector.

TM-4 EOD SEARCH ASSURANCE

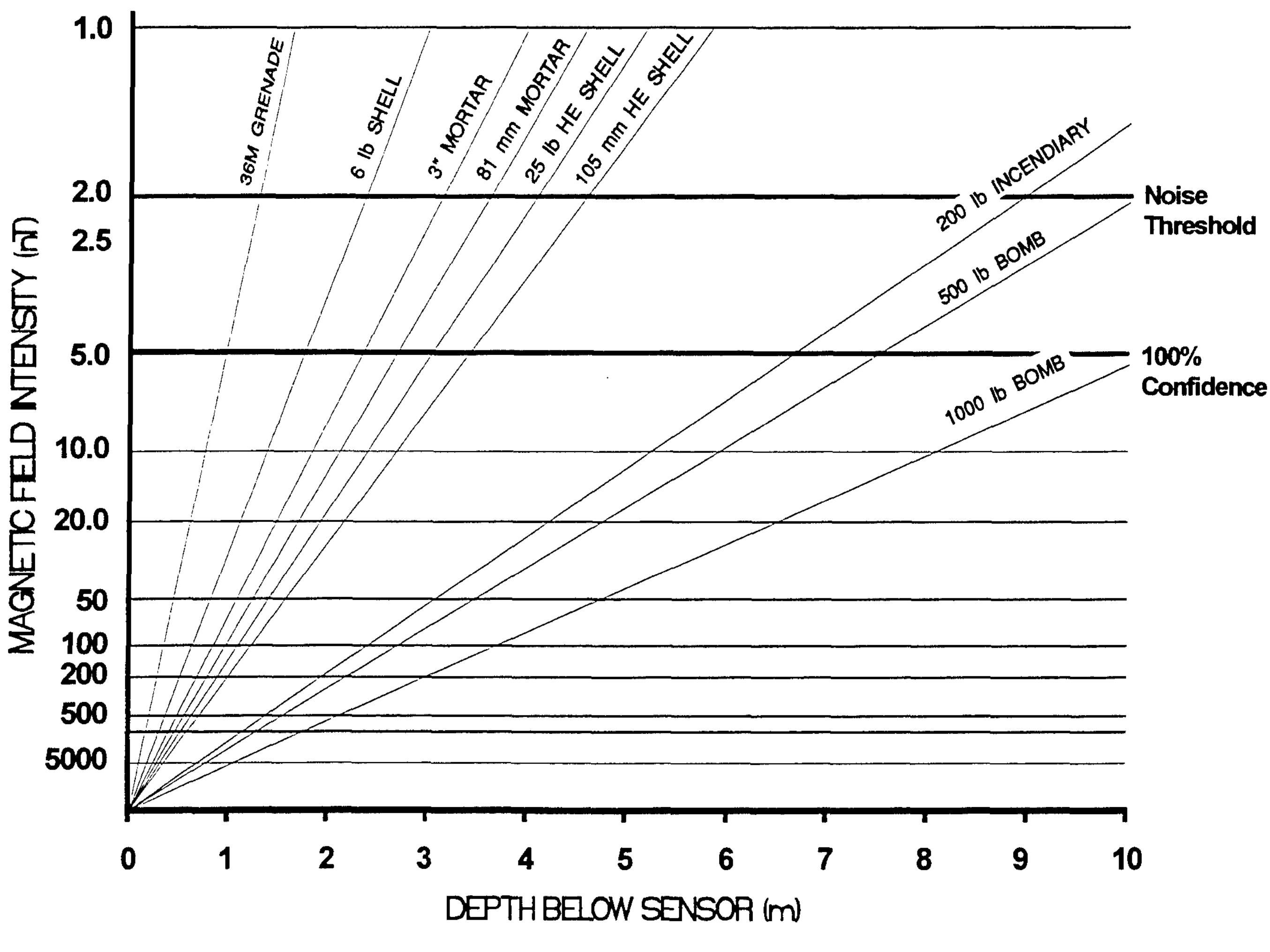

FIGURE 2 A graph plotting the typical magnetic signal amplitude as a function of depth below a magnetic sensor for a range of UXO types. This graph may be used to represent the detection depth achieved with a nominated assurance probability, given a known survey sampling specification and known magnetic noise from geological, cultural, or electromagnetic sources. In this example, "100 %" assurance means the risk of an item remaining undetected within this depth is "insurable"; nominally less than 1 in 100,000.

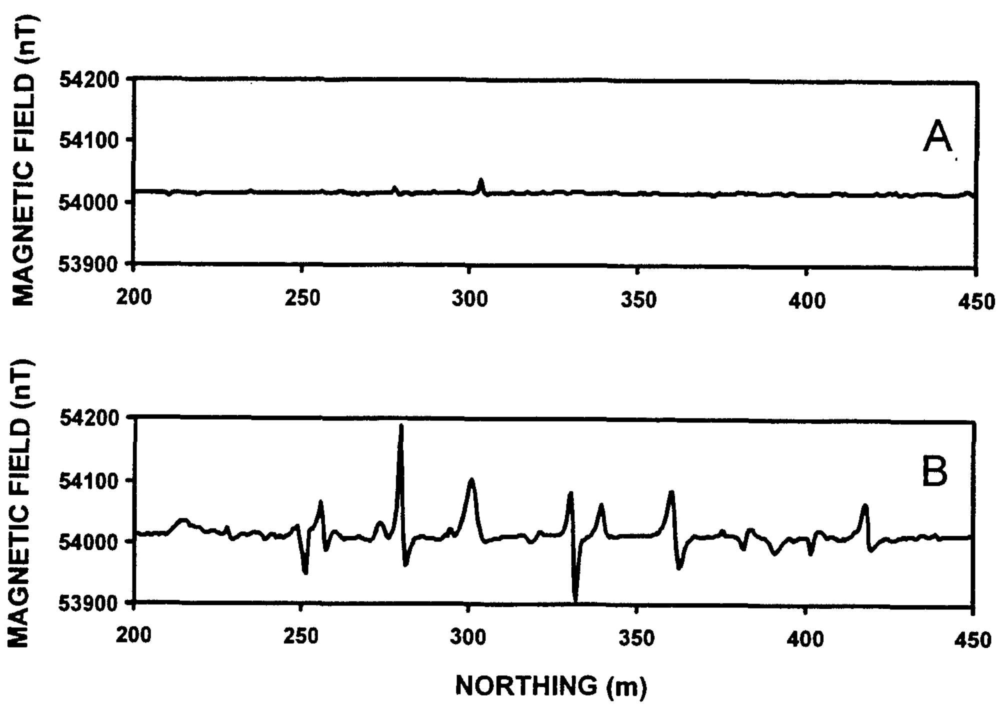

FIGURE 3 Two magnetic profiles, each displaying a distinctly different magnetic signature. Profile "A" displays a low amplitude "noise only" signature while profile "B" contains low amplitude noise plus a pattern of dipolar features characteristic of UXO contamination.

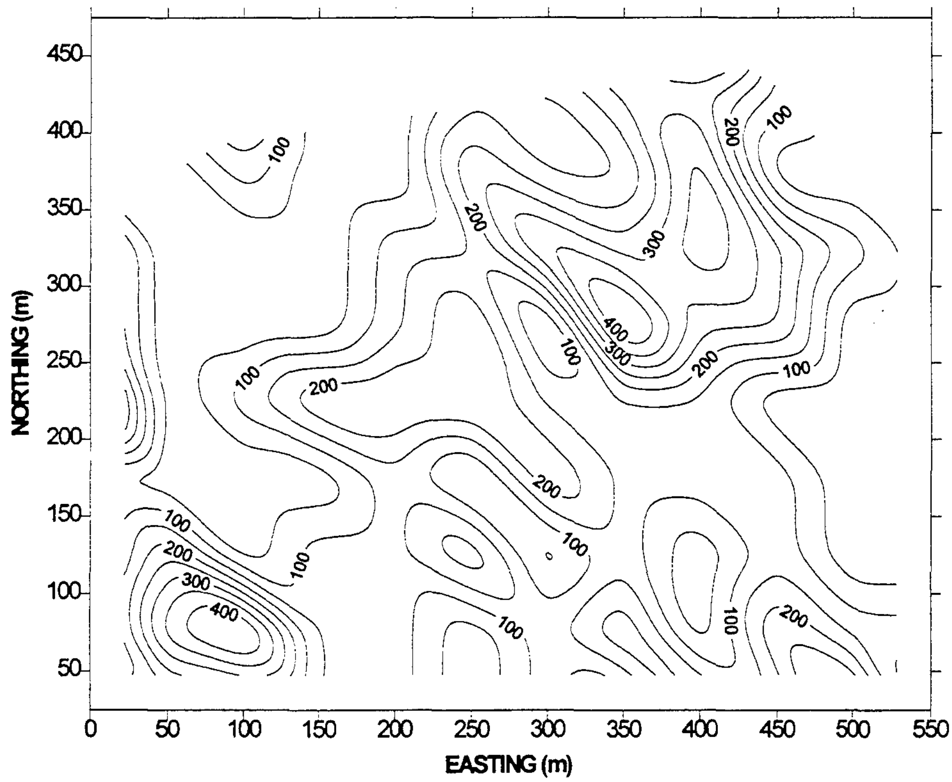

FIGURE 4 A contour map of the ferrous items per Ha determined from a "reconnaissance" specification site assessment survey in which data were recorded with a TM-4 magnetometer at 0.8 m sensor elevation, 0.2 m sample interval and 50 m line spacing. Contamination ranging from less than 50 items per Ha to just over 400 items per Ha near the target centre was mapped.

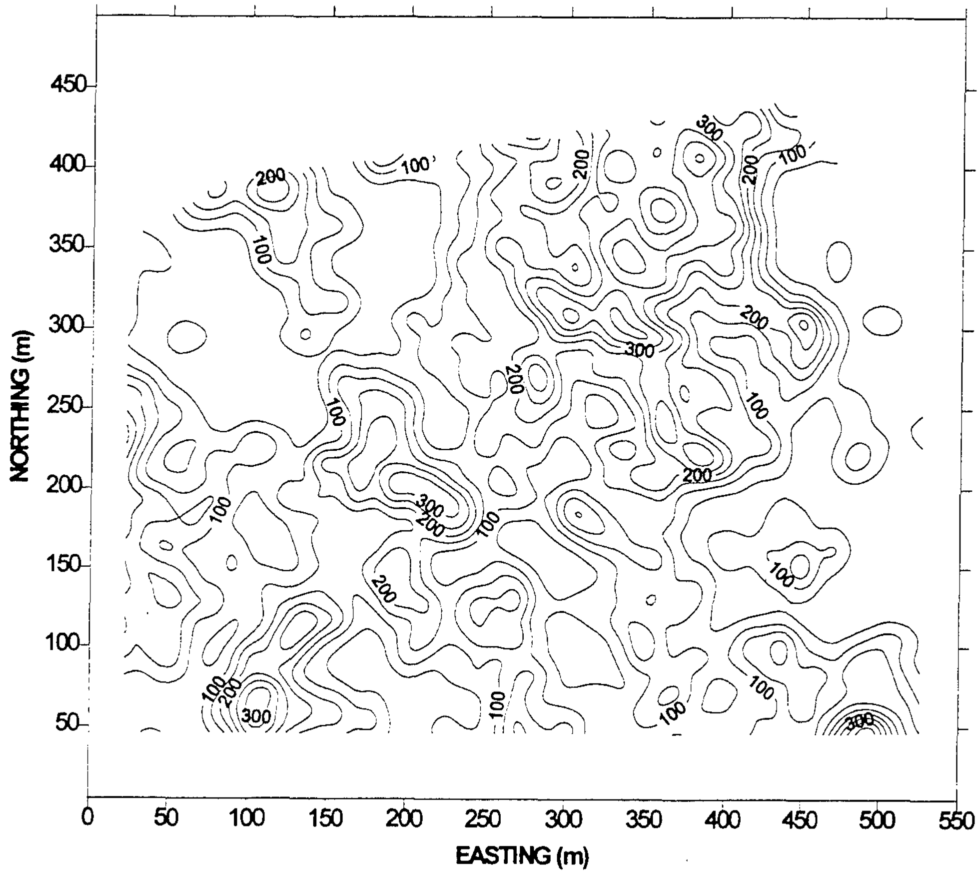

FIGURE 5 A contour map of ferrous contamination determined from a "detailed" survey specification, in-filled to 10 m line spacing. Resolution of the contaminated areas has been improved over that achieved with the reconnaissance survey data.

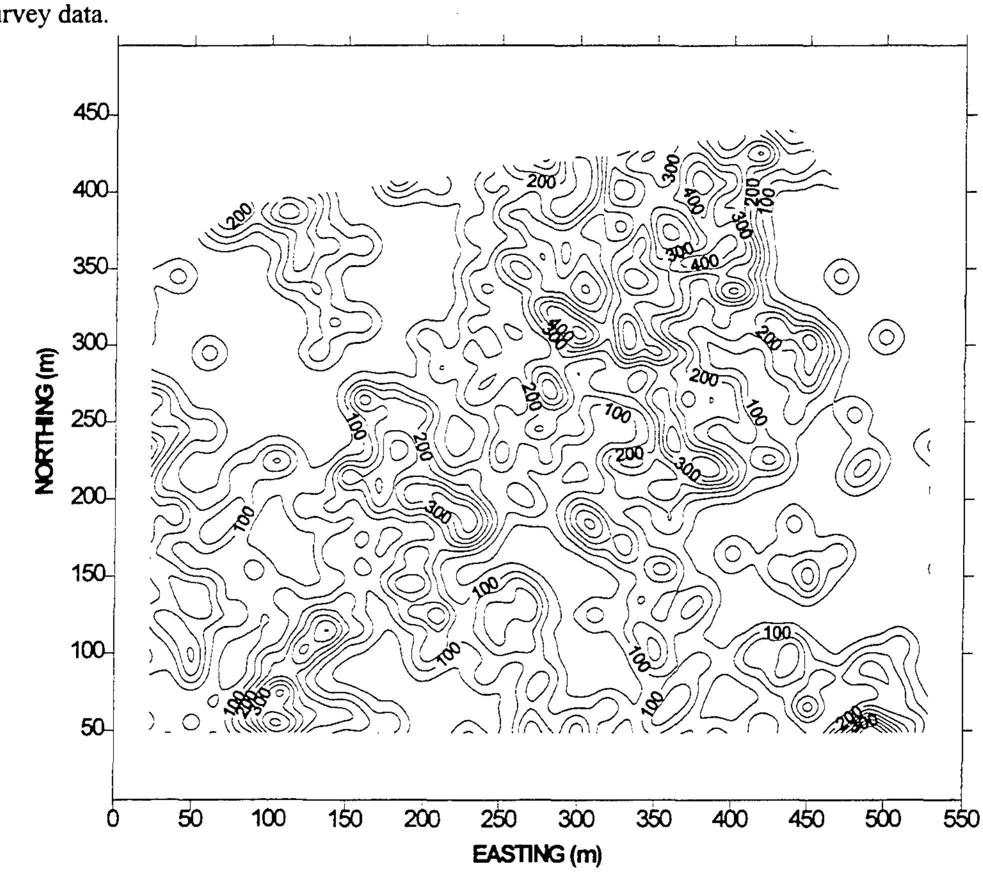

FIGURE 6 A contour map of ferrous contamination determined from a fully specified survey, conducted at 1 m line spacing. The "true" contamination distribution can be seen.

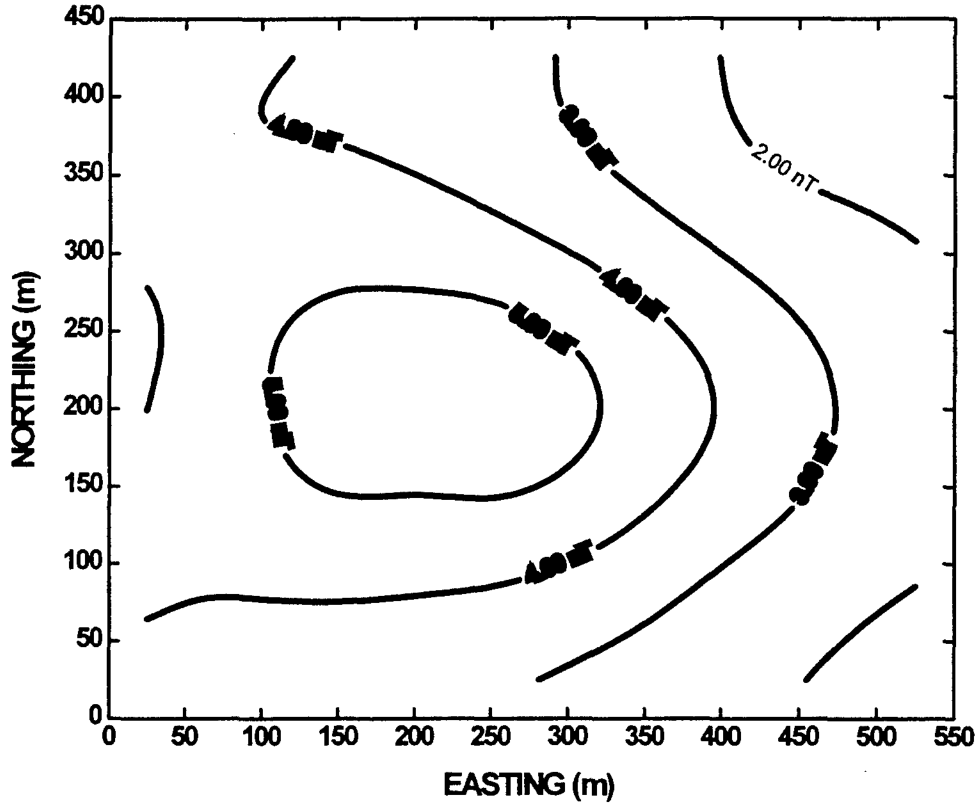

FIGURE 7 An example of a contour map of noise envelope amplitude expressed in nT peak to peak. When used in conjunction with the data graphed in Figure 2, the detection depth for any UXO type may be determined at any location in the area surveyed.

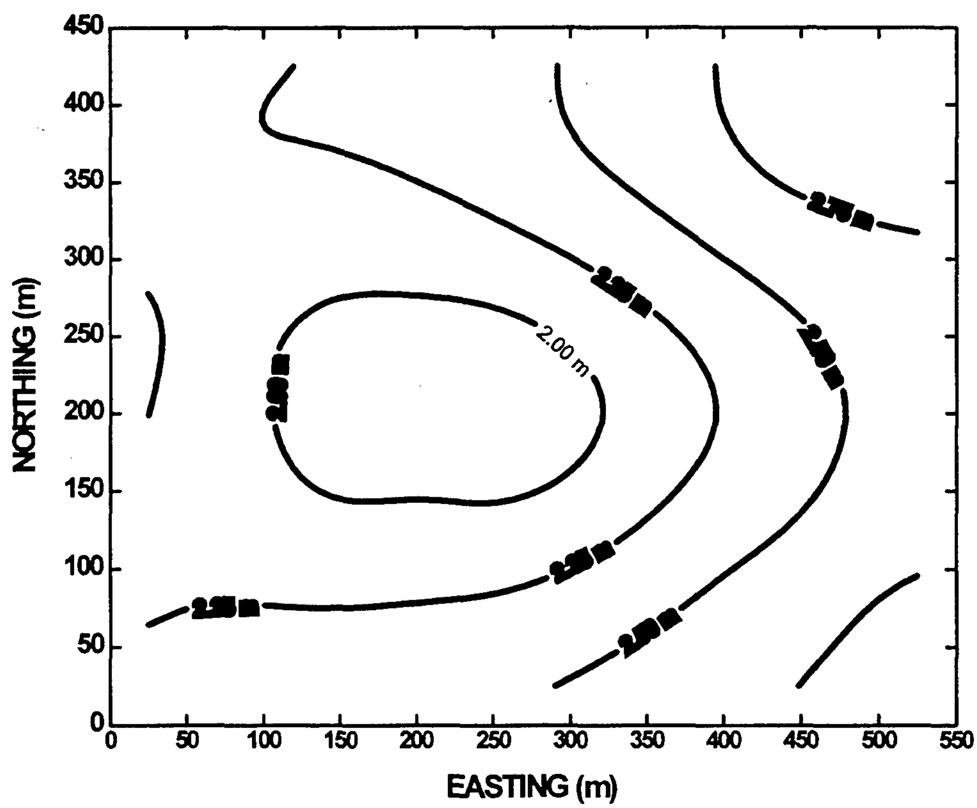

FIGURE 8 A contour map derived from Figures 2 and 7 representing the depth to which a 105 mm HE projectile may be detected with "100%" confidence.

EMERGENCY DEMOLITION SYSTEM

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ABSTRACT

Occasionally, a munition is recovered at a former test site containing a chemical agent fill, an explosively filled burster tube, and an unstable fuse. Currently, these munitions can only be handled by the use of open burn/open detonation (OB/OD) methods. This technique requires the use of 5 pounds of explosive for every pound of chemical agent. Due to the quantity of explosives required, evacuation would be required if the munition was located in a populated area. Although OB/OD has been shown to be safe, the Army will only use OB/OD when there are no other options. This is due to concerns from the public as well as environmental issues.

Sandia National Laboratories (SNL), under contract with the US Army Project Manager for Non-Stockpile Chemical Materiel (PMNSCM), is developing a mobile system for environmentally acceptable and safe disposal of these munitions. This system will be designed to destroy the fuse and burster without causing a high order detonation. After the explosive threat has been removed, the chemical fill will be treated so that it can be safely disposed of. The system will include an environmentally sealed, explosion proof chamber to safeguard the environment in the case of an unintentional high order detonation of the burster.

The Emergency Demolition System (EDS) is currently in its early concept stage. At this time, the most promising candidate for destroying the fuse, and breaching the munition is the use of shaped charges. A conical shaped charge would be aimed at the fuse. A linear shaped charge would be used to breach the munition. This will expose the chemical agent as well as unconfine the explosive in the burster well. The three most promising methods for the t

reatment of the chemical agent are neutralization, incineration, and Super Critical Fluid Oxidation (SCFO). The first two methods are technologies that are well defined. The third method is promising for treating both chemical agents and explosives, but will require more development than either incineration or neutralization.

BACKGROUND

PM NSCM is responsible for the disposal of buried Chemical Warfare Material (CWM), CWM remaining on former firing ranges, recovered CWM, binary CWM, former chemical warfare production facilities, and miscellaneous components manufactured specifically for use as or with chemical weapons. In order to address the problem of disposing of recovered CWM, PM NSCM is developing an integrated family of mobile systems capable of rendering the CWM safe for commercial disposal. In all cases, these systems will be designed to travel to the site where the CWM is located. The CWM will be treated in-situ. PMNSCM is currently developing five mobile systems which are briefly described below;

Rapid Response System

The Rapid Response System is being developed to neutralize and dispose of Chemical Agent Identification Sets (CAIS). CAIS were training aids used by the military to train soldiers for the chemical warfare arena.

Munition Management Device-1

The Munition Management Device-1 (MMD1) is being developed to neutralize and dispose of non-explosively configured, chemically filled munitions. The MMD1 will handle munitions from small bomblets and 4.2 inch mortars to 500 pound bombs.

Munition Management Device-2

The MMD2 is being developed to neutralize and dispose of explosively configured, stable, chemically filled munitions. The MMD1 will handle munitions from small bomblets and 4.2 inch mortars to eight inch munitions and 125 pound bombs.

Munition Management Device-3

The MMD3 is being developed to neutralize and dispose of bulk chemical containers such as ton containers. In addition, the MMD3 will handle non-explosively configured 500 and 1000 pound bombs.

Emergency Demolition System

The Emergency Demolition System (EDS) is being developed to neutralize and dispose of explosively configured, unstable, chemically filled munitions. The EDS will handle munitions from hand grenades and 4.2 inch mortars to eight inch munitions.

EMERGENCY DEMOLITION SYSTEM

Purpose

The Purpose of the EDS is to treat chemically filled, explosively configured, fuzed, unstable munitions that have been recovered either from burial sites or firing ranges. The term "unstable" refers to the fuze condition either being in the "fire" position, or deteriorated, as determined by X-Ray. The EDS would begin processing munitions after they have been recovered, analyzed and placed in temporary storage. Due to restrictions on the shipment of CWM, it is envisioned that the storage and treatment of the CWM will take place near the recovery site. All processing of the munition will take place in a sealed, explosion proof chamber to protect the environment from blast and chemical hazards. A list of munitions processed in the EDS is listed in Table 1.

Table 1. EDS Munitions

1. 4 Inch Stokes
2. 4.2 Inch Mortar
3. Livens Projectile
4. 75mm Artillery Shell MK II
5. 4.7 Inch Artillery Shell MK II
6. 5 Inch Artillery Shell MK VI
7. 155mm Artillery Shell, Howitzer, MK II, MK IIa, and MK VII
8. 8 Inch Artillery Shell, MK III
9. French Chemical Hand Grenade

Chemical Fill Treatment

This report will focus on the use of shaped charges to gain access to the chemical fill and explosives in the ammunition. The treatment of the chemical fill will be covered in detail in EMERGENCY DESTRUCTION TECHNOLOGIES FOR RECOVERED, EXPLOSIVELY CONFIGURED, CHEMICAL WARFARE MATERIEL.

Shaped Charge Access

In order to gain access to the chemical fill as well as destroy the explosive components of the munition, the EDS employs both linear and conical shaped charges. In general, the approach is to use linear shaped charges for opening the munition case and conical shaped charges for accessing the burster well.

Linear Shaped Charges

The linear shaped charge (LSC) differs from the conical in that the jet is formed from the collision of two plates rather than from the collapse of a cone. This is achieved by constructing the charge in a chevron cross-section shape with a long axial dimension perpendicular to that. This is shown in Figure 1.

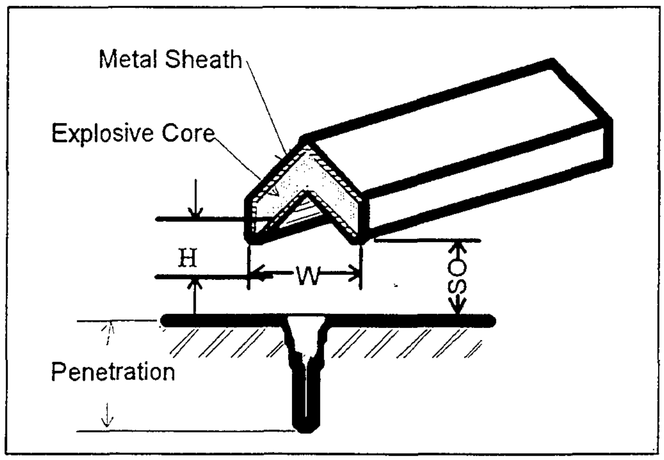

Figure 1 Configuration and critical parameters for Linear Shaped Charge.

The jet formed from the linear shaped charge is like a long knife blade. It behaves the same as the jet from a conical shaped charge except that it cuts a long groove or channel in a target rather than a conical hole. Most linear shaped charges are manufactured by impact or linear extrusion. Typical sheath (and hence liner) materials are lead, copper or aluminum, explosive fillers are typically RDX or HNS. Approximate loading and performance are (referring to Figure 1):

$W \approx C^{1/2} / 32$ (W in inches, C is the core loading in grains per foot)

$H \approx W / 4$

SO (optimum) $\approx 0.2W$ (for lead sheathed)

$\approx 0.7W$ (for copper sheathed)

$\approx 1.0W$ (for aluminum sheathed)

Penetration into steel $\approx 0.6W$ (for lead sheathed)

$\approx 0.7W$ (for aluminum sheathed)

$\approx 0.9W$ (for copper sheathed).

These relationships are based on averages for manufacturers data for their products. A sample of such data is shown in Figure 2 where we see penetration in steel plotted versus CLSC core load for charges manufactured by Jet Research Center (JRC) in Arlington, Texas.

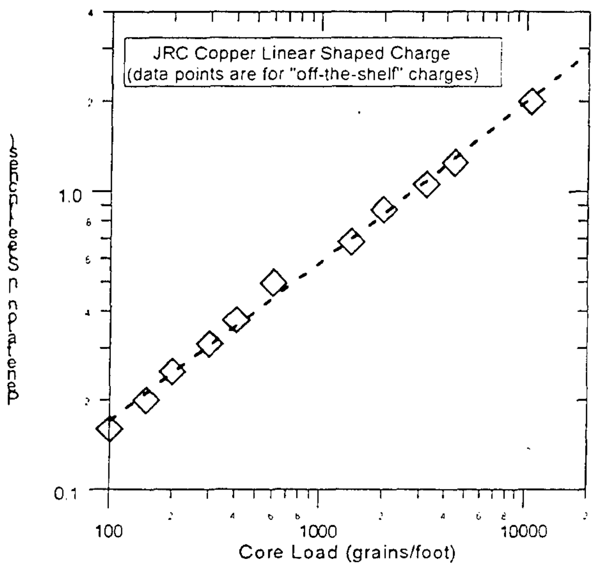

Figure 2 Penetration depth in steel targets by CLSC of various core loadings.

Using the above equations, the required charges for penetrating the munition bodies of interest can be calculated. Table 2 shows these required charges.

Table 2. Sizes of CLSC Required for Opening Various Projectiles

PROJECTILE	WALL THICKNESS (inches)	CALCULATED CLSC CORE LOADING (grains/foot)	AVAILABLE SHELF SIZE (grains/foot)	SPECIAL ORDER SIZE (grains/foot)
8 inch MKII	0.77	1676	1400	1600
155mm	0.615	1101	1400	1100
6 inch MKIII	0.53	834	600	800
5 inch MKVI	0.48	693	600	700
75mm MKII	0.303	293	300	300

Design problems .i.e. reliability problems exhibit themselves at joints and interfaces. It is preferable to initiate LSC from the ends and to make the entire charge of a single length, avoiding joints . Such a design is shown in Figure 3.

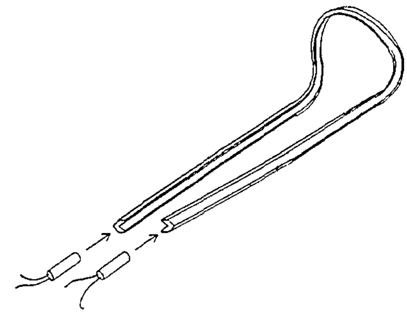

Figure 3. A cutting charge of LSC configured in a single piece.

The charge shown in Figure 3 would be used to cut an artillery shell into two pieces as shown in Figure 4.

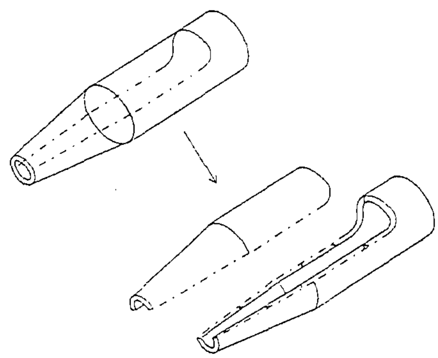

Figure 4. LSC used to make a two piece cut on an artillery projectile

LSC assemblies using joints and corners can be used to make more complex cuts if required.

Conical Shaped Charges

A typical conical shaped charge (CSC) is shown in Figure 5. The liner material is usually copper, aluminum, or mild steel, although glass is also sometimes used. The explosive is usually pressed or cast. The charge works by explosively collapsing the liner, which forms a high-velocity jet of liner material. The formation of the jet is rather complex to model mathematically, so let us look at the phenomena empirically as we did above with the behavior of linear charges.

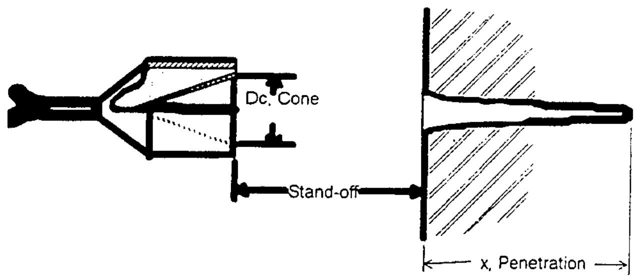

Figure 5 A typical conical shaped charge

Jet Formation

As the explosive detonation wave passes over the liner, the liner is accelerated at some small angle to the explosive liner interface. When the liner material converges at the center line (or axis) of the charge, the surface material is squeezed out at high velocity. This "squeezed-out" material forms the jet. Nearer the apex of the cone, the ratio of the liner mass to charge mass is lower and therefore the liner velocity is higher. Since the material closest to the apex was at higher velocity, the portion of the jet that comes from that area is also highest in velocity. Therefore, we have a jet with a velocity gradient, the leading tip is moving faster than the rear. Laboratory experiments have shown that this gradient is linear for most CSCs. Since there is a velocity gradient along the jet, the farther it travels, the longer it gets. Many of the particles that form the jet have slightly different directions of flight because of minor inhomogeneities in the charge and liner and small hydrodynamic instabilities during the jet formation. After travel of several diameters (of the original charge), the jet begins to noticeably break up.

Effect on Target

The erosion of a target by a penetrating jet is very similar to what one sees when a stream of water from a hose is squirted into a bank of dirt. Material dislodged at the deepest part of the hole turns to mud and flows back along the walls of the hole. Metal targets under shaped-charge jet attack behave like fluids because at the impact velocities of the jet, both jet and target at the interface are at several megabars pressure, well into the plastic material properties region for almost all materials. This erosion process continues until the entire jet has been used up or until the target has been perforated.

Effect of Stand-off

Stand-off is defined as the distance of the base of the charge from the target. This is usually expressed in charge diameters. At very short stand-offs, the jet is still very short; it has not had time to form, or "stretch," therefore penetration into the target is less than optimal. At very long stand-offs, the jet is breaking up and each particle is hitting farther and farther off center and is not contributing to the penetration at the center of the target.

Shelf Hardware

Many shaped charges, both commercial and military, are available "off-the-shelf." Some are far more efficient than others in relation to depth of penetration as a function of size or explosive weight. This spread of penetration efficiency is due, not to poor design, but because each charge was designed for a particular application, and not all were optimized with penetration alone in mind. Figure 6.8 presents the performance of a number of different shaped charges, showing the ranges one should expect of penetration versus weight of charge based upon what is available off-the-shelf. The correlation shown for penetration versus charge weight should, by scaling theory, be a function of $W^{1/3}$, not $W^{2/5}$ as seen in this figure. This observed deviation from normal scaling is probably due to more attention paid to weight efficiency for larger charges than for very small ones.

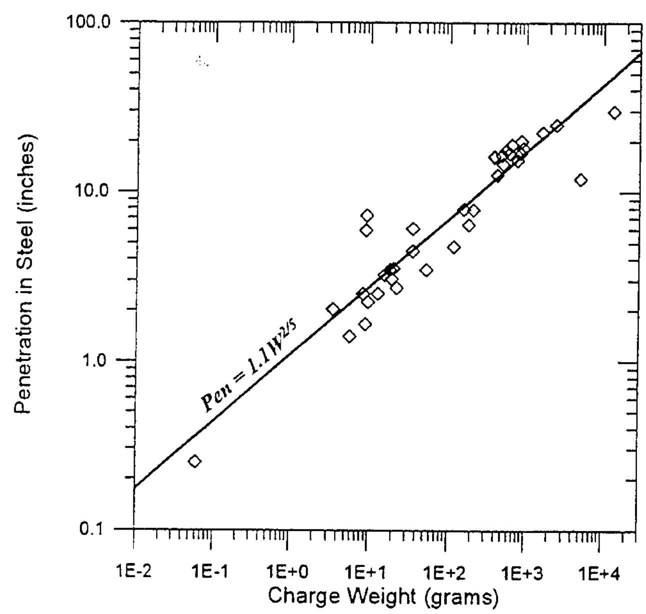

Figure 6. Penetration versus charge weight for a number of different CSCs.

Although different conical shaped charges have designs which are optimized for different applications, the average or generic relationships among the design and performance parameters fall into fairly predictable bounds. On average, the following apply:

$$L_j \approx 4.5D_c,$$

$$D_j \approx 0.1D_c - \frac{0.05D_c}{L_j}L_x,$$

$$v_x \approx 1.5 + \frac{6L_x}{L_j},$$

$$\Delta L_x = \Delta x_i\left(\frac{\rho_i}{\rho_j}\right)^{1/2},$$

$$L_x = L_j - \sum_i \Delta x_i\left(\frac{\rho_i}{\rho_j}\right)^{1/2}, and$$

$$W_c \approx 0.0335D_c^{3.3},$$

where: L_j is the jet length at optimum stand-off,
D_c is the base diameter of the conical charge liner,
D_j is the diameter of the jet at position Lx along the length of the jet,
L_x is the remaining length of the jet after penetrating a target,
v_x is the velocity of the jet at position L_x,
Δx is the thickness of target penetrated,
ρ_i is the density of the particular target penetrated,
ρ_j is the density of the jet material, and
W_c is the weight of explosive in the shaped charge.

In order to achieve prompt initiation of HE by the impact of a shaped charge jet, the product of the square of the jet velocity times the diameter of the jet (at the impact conditions) must be greater than some critical constant for that particular HE.

$$\left(V^2D\right)_{crit} = \text{constant},$$

where V is the impact velocity of the jet at the HE surface, and D is the diameter of the jet at that surface. The value of the constant is different for different explosives as well as for different conditions of any specific explosive. The constant, in essence, is a measure of the shock sensitivity of the explosive, and the conditions which are of importance are density, purity, crystal size and morphology, porosity and perhaps several others.

By applying the general relationships shown above to the case where a conical shaped charge jet is shot through the wall of a projectile which is Δx_1 thick, and then continue through a filler agent, Δx_2 thick and then into the burster explosive, a single closed form equation is obtained relating the base diameter of the shaped charge to the various parameters given above:

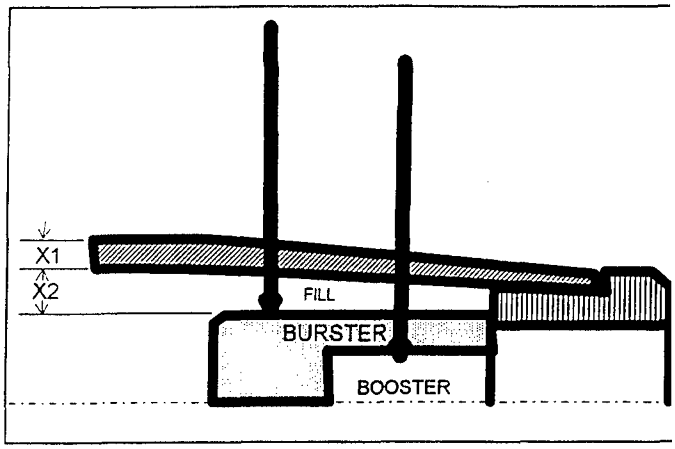

Figure 7 Two different jet paths through the side of a projectile and into the burster.

By applying the general equations and assuming that jet diameter is constant and equal to 7% of the base cone diameter, the following equation is derived:

$$0 = 54.2D_c^2 - \left[\left(V^2D\right)_{crit} + 20\Phi\right]D_c + 1.78\Phi^2 \quad .$$

Using equation the requirements for minimum shaped charge size to guarantee detonation of the burster by fixing the assumed critical V^2D value and specifying the shell dimensions (also assuming that the filler density is 2 g/cm^3) can be calculated. The results of that calculation are seen in Table 3.

Table 3. Conical shaped charge size required to achieve V^2D_{crit} in various projectiles.

PROJECTILE	Wall, Δx_1 inches	Filler, Δx_2 inches	V^2D_{crit} in(km/s)^2	D_c inch	W_{HE} gram
w/TNT Burster					
8inch MKIII	0.77	1.5	8	2.12	180
155mm	0.615	1.2	8	2.10	175
6inch MKIII	0.53	1.2	8	2.09	174
5inch MKVI	0.48	1.0	8	2.09	172
75mm MKII	0.303	0.6	8	2.07	166
w/Tetryl Burster					
8inch MKIII	0.77	1.5	3.4	0.947	12.6
155mm	0.615	1.2	3.4	0.930	11.9
6inch MKIII	0.53	1.2	3.4	0.926	11.7
5inch MKVI	0.48	1.0	3.4	0.917	11.4
75mm MKII	0.303	0.6	3.4	0.897	10.6

We see in the above table that the dimensions of the projectile have very little effect on the size requirement of the shaped charge. One size charge would do nicely for all projectiles.

Mechanical Design Requirements

The mechanical design for the system is envisioned as a curved receiving cradle tray with linear shaped charge (LSC) and conical shaped charge (CSC) charge holders attached to it along with sacrificial fragment catching plates. The latter are sized and positioned such that they will intercept all of the fragments generated by the shaped charges as well as those generated if the munition burster charge is initiated. These plates will be free to move, however due to their mass, their velocity will be much lower than the intercepted fragments and will be designed so that impact with the containment vessel walls will not create any damage to the vessel.

MUNITIONS MANAGEMENT DEVICE 2 FOR EXPLOSIVELY CONFIGURED CHEMICAL WEAPON MATERIEL

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ABSTRACT

The mission of the Project Manager for Non-Stockpile Chemical Materiel (PMNSCM) includes the requirement to safely dispose of recovered chemical munitions. A portion of these recovered munitions will contain a chemical agent fill and be explosively configured. Teledyne Brown Engineering (TBE), under contract to PMNSCM, has developed a concept for containing, accessing and neutralizing the contents of these munitions. TBE will design, fabricate and test the Munitions Management Device 2 (MMD2) to fulfill this mission.

The current concept being developed by TBE is a mobile system which will treat the recovered munitions in-situ. The munition would be placed in a holding vessel and then loaded into an explosion proof chamber. The munition would be drilled and the agent drained. The agent would be neutralized in an external reactor. Once the chemical fill has been removed, the interior of the munition will be flushed with a neutralization liquid to decontaminate the munition. After the munition has been decontaminated, it will be removed from the MMD2 and the explosives will be destroyed using conventional means.

The MMD2 is being designed to handle a variety of chemical filled weapons. These weapons include mortars, artillery shells, bombs, and rockets. The largest size weapon to be treated would be a 125 pound bomb containing 83 pounds of lewisite. The largest burster charge expected to be encountered is 7 pounds (Comp B).

BACKGROUND

PMNSCM is responsible for the disposal of buried Chemical Warfare Materiel (CWM), CWM remaining on former firing ranges, recovered CWM, binary CWM, former chemical warfare production facilities, and miscellaneous components manufactured specifically for use as or with chemical weapons. In order to address the problem of disposing of recovered CWM, PMNSCM is developing an integrated family of mobile systems capable of rendering the CWM safe for commercial disposal. In all cases, these systems will be designed to travel to the site where the CWM is located. The CWM will be treated in-situ. PMNSCM is currently developing five mobile systems which are briefly described below;

Rapid Response System

The Rapid Response System is being developed to neutralize and dispose of Chemical Agent Identification Sets (CAIS). CAIS were training aids used by the military to train soldiers for the chemical warfare arena.

Munition Management Device-1

The Munition Management Device-1 (MMD1) is being developed to neutralize and dispose of non-explosively configured, chemically filled munitions. The MMD1 will handle munitions from small bomblets and 4.2 inch mortars to 500 pound bombs.

Munition Management Device-2

The MMD2 is being developed to neutralize and dispose of explosively configured, stable, chemically filled munitions. The MMD1 will handle munitions from small bomblets and 4.2 inch mortars to eight inch munitions and 125 pound bombs.

Munition Management Device-3

The MMD3 is being developed to neutralize and dispose of bulk chemical containers such as ton containers. In addition, the MMD3 will handle non-explosively

configured 500 and 1000 pound bombs.

Emergency Demolition System

The Emergency Demolition System (EDS) is being developed to neutralize and dispose of explosively configured, unstable, chemically filled munitions. The EDS will handle munitions from hand grenades and 4.2 inch mortars to eight inch munitions.

MUNITION MANAGEMENT DEVICE 2

Purpose

The MMD2's purpose is to handle explosively configured, stable, chemically filled munitions that have been recovered from either burial sites or firing ranges. The term "stable" refers to the munition either not containing a fuze, or an X-Ray conformation that the fuze is in the "Safe" position and is not deteriorated. The MMD2 would begin processing these munitions after they have been recovered, analyzed, and placed in temporary storage. Due to restrictions on the shipment of CWM, it is envisioned that storage and treatment of the CWM will take place near the recovery site. The MMD2 design will utilize an explosion proof chamber to contain all vapors and fragmentation in the unlikely event that a munition were to explode during processing. A list of munitions which will be handled by the MMD2 is given in table 1.

Table 1
MMD2 Munitions

1. 4 Inch Stokes
2. 4.2 Inch Mortar
3. Livens Projectile
5. 75mm Artillery Shell MK II
6. 4.7 Inch Artillery Shell MK II
7. 5 Inch Artillery Shell MK VI
8. 6 Inch Artillery Shell MK III
9. 5 Inch Chemical Shell MK 53
10. 5 Inch Chemical Shell MK 54
11. 155mm Artillery Shell Howitzer MK II, MK II, MK IV
12. 175mm Artillery Projectile, Gun T-223
13. 8 Inch Artillery Shell MK III
14. 8 Inch Artillery Projectile, T-174
15. 2.36 Inch Rocket, M26
16. 7.2 Inch Rocket, M 24 and M 27
17. 3.5 Inch Rocket, Agent Kit, E8
18. 5 Inch Rocket Warhead, MK 40
19. 5 Inch Rocket, MK 40
20. 10 Pound Gas Bomb, M125A1
21. 30 Pound Gas Bomb, M1
22. 100 Pound Bomb, M47 and M47A2
23. 100 Pound Bomb, MK 42
24. 115/125 Pound Bomb, E-46, E52, M70, M70A1, and M113
25. Bomblet, M139
26. 3.4 Pound Bomblet, M134
27. Bomblet, E139
28. Bomblet, BLU/50/B
29. Traktor Rocket

Description

The primary design concept for the MMD2 system consists of three trailers (See Figure 1). The first trailer is a flatbed which holds an explosion proof chamber. Inside of this chamber (See Figure 2) is a drill and extract mechanism which will enable the operator to drain the agent out of the munition for processing. The second trailer (See Figure 3) contains the chemical process equipment which will neutralize the agent. The third trailer will house the control system as well as other components. In addition to these three trailers, there will be additional trailers to house support functions such as munition assessment, analytical laboratory, personnel decontamination, change rooms, etc. In order to allow for an extra level of chemical containment, the explosion proof container and the process trailer will be located under an environmental enclosure.

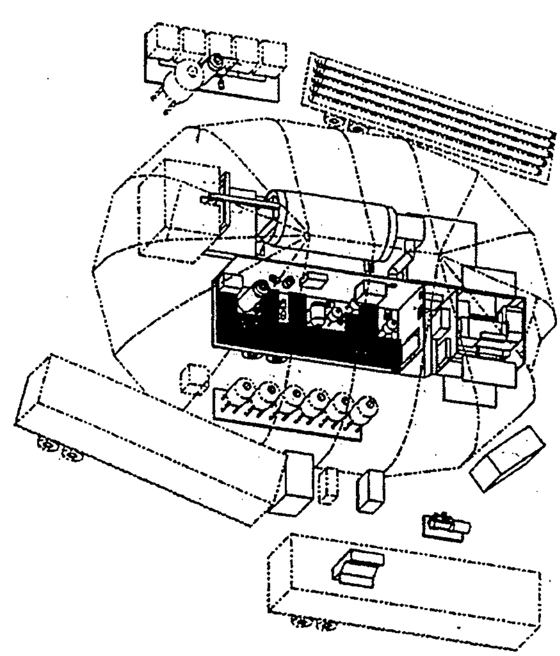

Figure 1 MMD2 System

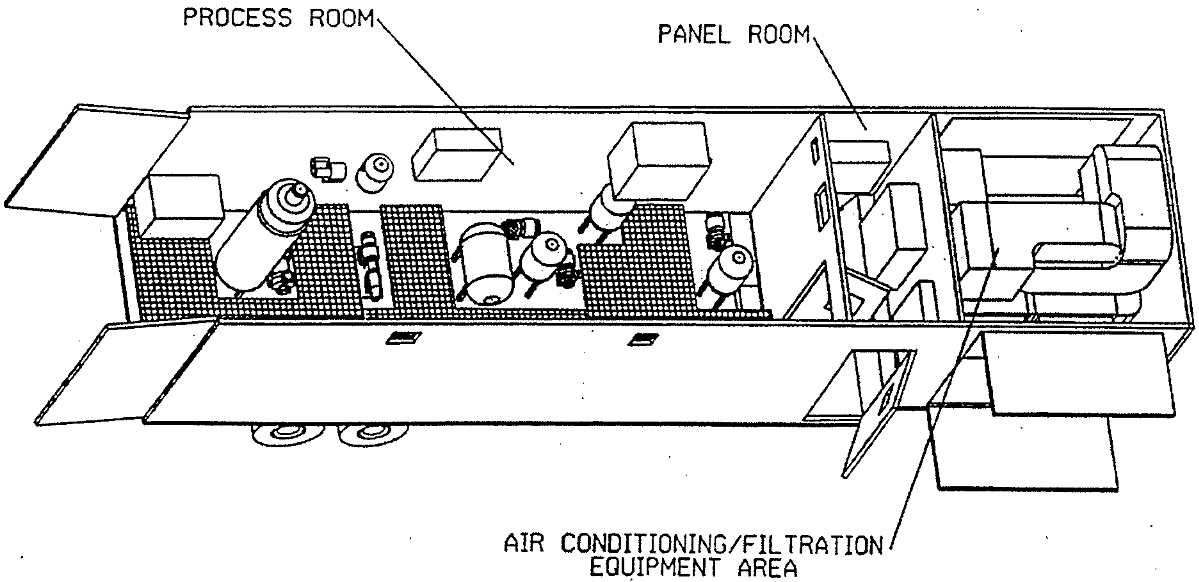

Figure 3 Chemical Process Trailer

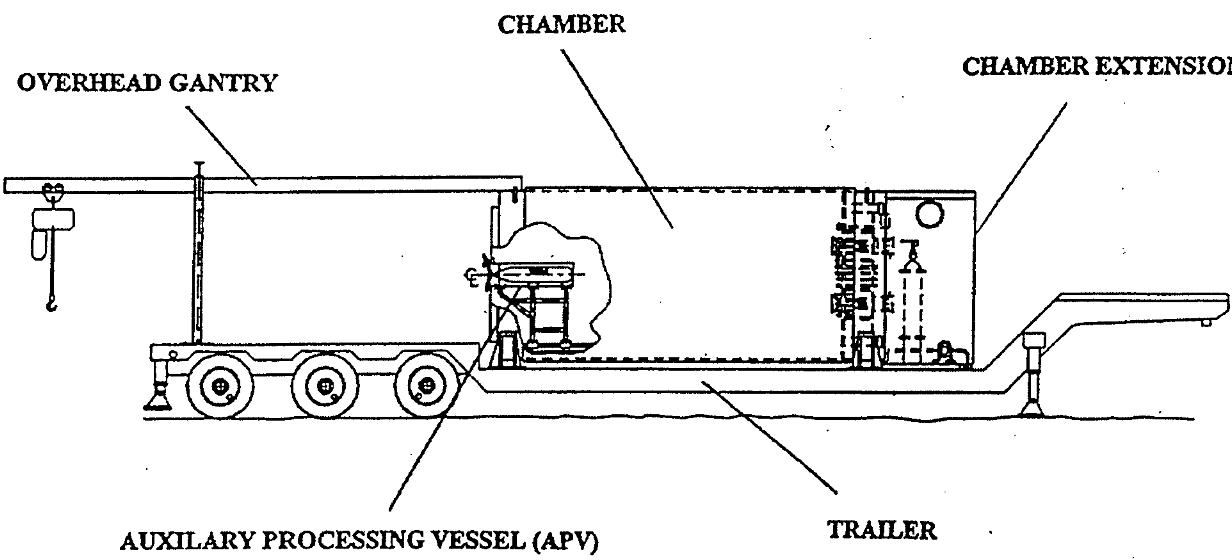

Figure 2 Munition Process Trailer

Munition Processing Trailer

The Munition Processing Trailer is designed to contain munition fragments and agent vapor in the unlikely event of an explosion, access the chemical agent in the munition, drain the munition agent fill and decontaminate the munition casing. The key components of this trailer are an explosion containment chamber, an Auxiliary Processing Vessel (APV), and a drill and extract mechanism.

The Explosion proof chamber (see Figure 4) is being sized to contain the APV, and the drill and extract mechanism. The chamber is designed to contain an explosive blast of 13.025 pounds with out leaking vapors to the outside atmosphere. The 13.025 pound limit was chosen to provide

an adequate factor of safety above the largest explosive burster found in the munitions listed in table 1. The chamber design features two concentric tubes with a glycol/water layer in between. The outer skin is .591 inches thick and the inner skin is 1.18 inches thick The glycol/water jacket is 1.18 inches thick. The chamber features a double front door. The inner door swings inward and is 2.76 inches thick. The outer door slides and is 1.5 inches thick. The chamber is constructed from WELDOX 500 D steel.

At this time, the design and analysis of the chamber has been completed. The analysis was performed using a finite element model of the chamber and the blast pressure shock wave. The blast wave analysis started with a 1-D pie shaped grid. The shock wave was allowed to propagate until it encountered the first structure. At that time, the parameters were remapped into a 2-D model. The results of the analysis showed that after 10 milliseconds the blast reflections have begun to diminish. The maximum peak pressure at the cylindrical wall was 1524 psi at .5 ms. The maximum peak pressure at the endplate was 1086 psi at 1.8 ms. The maximum chamber stress was 39.7 ksi, well below the allowable yield stress of the material.

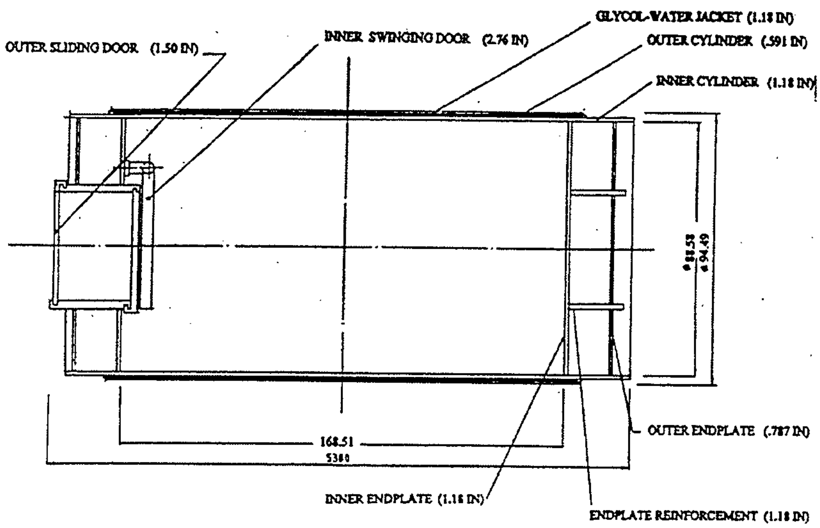

Figure 4 Explosion Proof Chamber

In addition to a stress analysis, a fragmentation and penetration analysis was performed. Fragment masses and velocities were approximated using Gurney-Sarmousakis equations. These equations are based on empirical data. They relate the ratio of charge to munition casing weight to fragmentation size and velocities. The required thickness to resist penetration was derived using the Grabarek equation. The analysis was performed with several conservative assumptions made; No fragmentation suppression, slender aspect ratios for the fragments, no rotational velocity, impacts perpendicular to the surface, and munition entirely filled with explosive. The analysis showed that the worst case required plate thicknesses to resist penetration were .833 inches for the inner wall and .239 inches for the end plates. Both of these are below the thicknesses in the explosion containment vessel.

The APV is used to hold the munition inside of the explosion containment vessel (See Figure 5). It is designed to mate to the drill and extract mechanism (See Figure 6). The APV has a top and bottom access hole through which the drills enter. If the munition were to leak during the drill and extraction process, the APV would limit the chemical contamination from reaching the explosion containment vessel.

The drill and extraction mechanism consists of two drilling machines. They are mounted to the top and the bottom of the APV. This mechanism drills a top and bottom hole in the munition. The bottom hole is used to suction the agent out of the munition. The top hole is used to introduce decontamination fluid into the munition.

Chemical Processing Trailer

After the agent has been extracted from the munition, it is transferred, via flexible double walled piping to the chemical processing trailer. The chemical process trailer contains an agitated, cooled and heated reactor, a gas knock out drum, a gas relief vessel and several surge tanks. In addition, the chemical process trailer contains a heating ventilation and filtration system. The agent is neutralized in the reactor and the neutralized wastes are packaged in DOT approved drums for shipment and disposal. The agents to be neutralized along with the neutralization fluid is listed in Table 2.

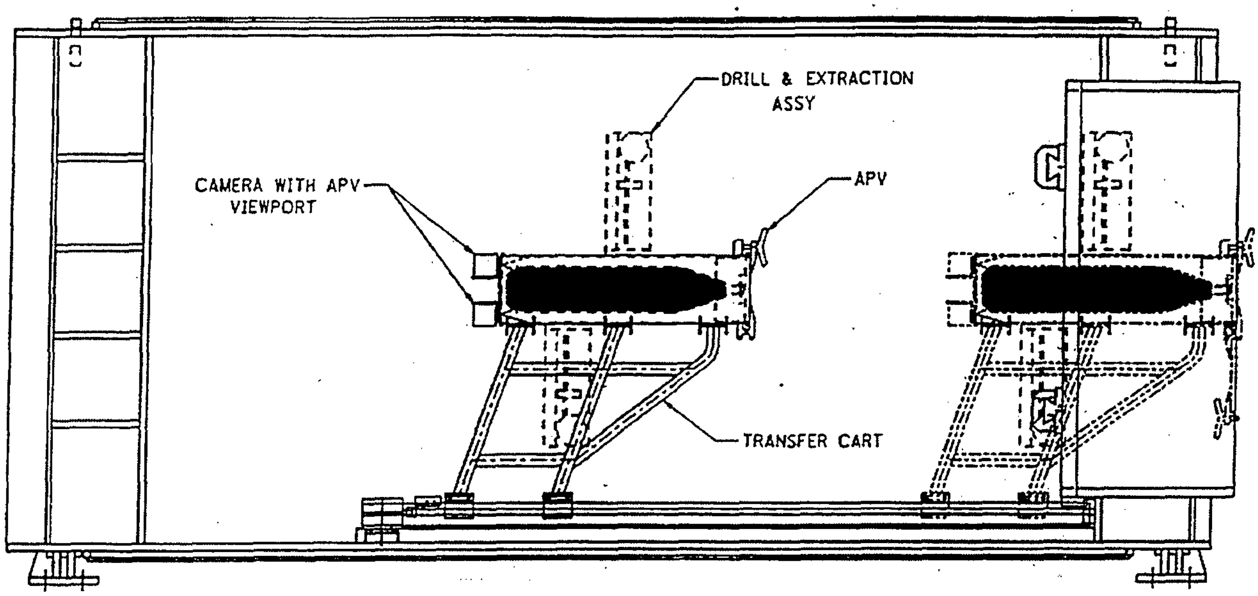

Figure 5 Auxiliary Process Vessel

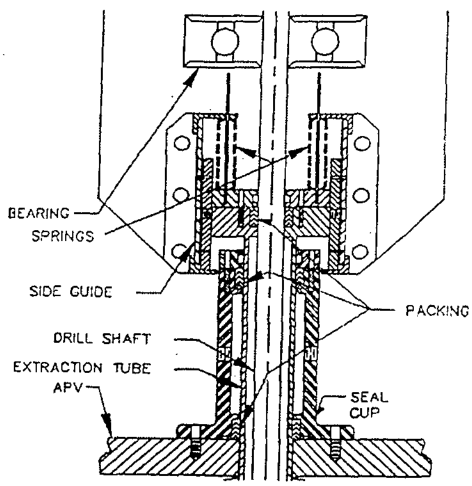

Figure 6 Drill and Extract

Table 2
Agents and Neutralization Fluids

Primary Agents	Neutralization Fluid
Mustard	Monoethanolamine
VX	Monoethanolamine and Caustic
GB	Monoethanolamine
Phosgene	Sodium Hydroxide
Cyanogen Chloride	Sodium Hydroxide

Explosive Components

The munitions treated in the MMD2 will contain a burster charge (See Figure 7). This burster charge is contained in a central burster tube. The largest burster charge is 7.3 pounds in the 8 inch artillery projectile. Once the agent has been removed from a munition and the interior decontaminated, the munition would be removed from the APV and the explosion containment vessel. It would then be placed inside of a separate explosion chamber where it would be detonated. After the detonation, the fragments would be collected and shipped for commercial disposal. At this time, this second explosion vessel has not been designed.

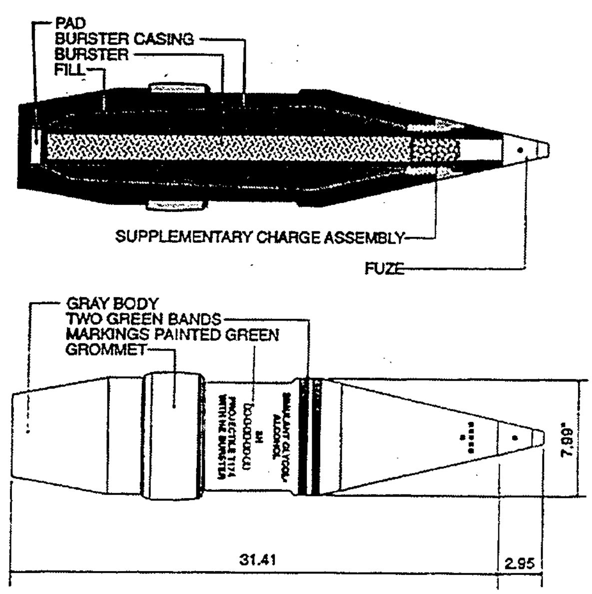

Figure 7 Munition

Operation Summary

A brief summary of the operations steps for the MMD2 follows. The assumptions made are that the munitions have been recovered, assessed, and stored. In addition, the site has been prepared and the MMD2 has been set up.

1. Remove munition from storage (still in container).
2. Remove munition from container and place on holding tray.
3. Reassess munition to verify chemical fill, internal configuration and explosive content.
4. Secure munition in APV.
5. Move APV into explosion containment vessel.
6. Close explosion containment vessel.
7. Drill upper hole.
8. Sample and confirm agent fill.
9. Drill lower hole.
10. Remove agent and transfer to holding tank.
11. Neutralization solution chosen.
12. Solution pumped into reactor.
13. Agent added while mixture is agitated (Heated or chilled as needed).
14. Continue agitation until analysis shows neutralization complete.
15. Mixture pumped to holding tank.
16. Decontaminate munition casing.
17. Mixture pumped to holding tank.
18. Open explosion containment vessel.
19. Open APV.
20. Remove munition casing.
21. Inspect casing for residue. Clean casing as needed.
22. Place casing in secondary explosion chamber.
23. Detonate burster charge.
24. Package casing for disposal.
25. Package neutralized mixture for disposal.

SUMMARY

The MMD2 system is being designed to dispose of chemically filled, explosively configured, stable munitions. Processing of the munition will take place in an explosion containment vessel. This vessel will protect personnel and the surrounding environment from both blast effects and agent vapors in the unlikely case of a detonation. The agent will be removed from the munition and neutralized in the process trailer. The explosive components will be detonated in a separate explosion chamber.

Vapor Containment Structure Development and Use

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ABSTRACT

The U.S. Army Engineering and Support Center, Huntsville is actively involved in the location and removal of buried unexploded munitions at formerly used defense sites (FUDS). In many cases, these munitions include liquid filled rounds which may contain hazardous chemical agents. A critical parameter for safety siting is the downwind hazard in the event of an accidental detonation of a chemical munition. An extensive test program has been conducted to determine the effectiveness of using a typical environmental vapor containment structure (VCS) over a munition removal site in controlling the downwind hazards resulting from the accidental detonation of a chemical filled munitions. This decrease in downwind hazards allows significant reductions in the required evacuation distance. Tests were conducted using replica scale models of the "Livens" and the 4.7-inch munitions, filled with an inert agent simulant and detonated inside of a full scale typical steel arch confinement structure. These tests were required for deployment at Wesley Seminary in Washington, D.C., in the community of Spring Valley. Measurements were made of the internal shock and quasi-static pressures, external overpressures, and the interior and exterior simulant dosages. Prior to conducting of the confinement tests, limited arena tests were performed to determine the fragmentation hazards for each munition. As part of the arena tests, measurements were made of the side-on overpressures. A description of the containment structure, structural features of the structure pertaining to blast and chemical agent containment, the model munitions, as well as an overview of the tests conducted and a summary of the test results, are presented in this paper. In addition to the initial tests conducted specifically for the Wesley Seminary site, several other projects which were designed to enhance the usability of the VCS are currently under development. These include the development of a partial containment annex to the VCS, which uses open suction hoods near the release point with high suction flow rates to capture a non-explosive release of chemical agent. The partial containment system (PCS) is to be used in removal operations where the possible chemical release is to be non-explosive and a total containment system such as the VCS cannot be used. This project is under development for use at the Former Santa Rosa Army Airfield in California for a possible chemical release from chemical agent identification kits. The paper will discuss the development and testing of the PCS. Another refinement of the VCS is planned to clearly define the limits and use of the VCS for a generic chemical ordnance item. This will be accomplished by first conducting tests to establish the maximum explosive quantity for the VCS and then determining the VCS capture efficiency for a variety of explosive quantities up to the explosive limit. A discussion of the proposed effort will be included in this paper. All efforts were and are conducted in support of the Huntsville Center's Ordnance and Explosives Army Mandatory Center of Expertise and the Innovative Technologies Program.

1.0 INTRODUCTION AND BACKGROUND

The U.S. Army Corps of Engineers (COE) is currently involved in the location and removal of buried unexploded munitions at formerly used defense sites (FUDS). In some cases these munitions will be liquid filled rounds which may contain hazardous chemical agents (CWM). A critical parameter for safety siting is the downwind hazard in the event of an accidental detonation of such a chemical round. The use of a vapor containment structure (VCS), in combination with a high efficiency particulate air (HEPA) filter and activated charcoal air filtration system, over the removal site can substantially reduce the downwind hazard.

On 5 January 1993, a civilian contractor uncovered a quantity of World War I munitions while digging a utility ditch for home construction in the Spring Valley community of Washington, D.C. An emergency response by the Army Explosive Ordnance Disposal (EOD) and the Army Technical Escort Unit (TEU) identified the munitions as possible chemical ordnance.

Operation Safe Removal was initiated to remove the ordnance. Phase I was completed by the end of January 1993 with a safe removal of 137 munition items. Phase II Operations were then initiated by the COE, Baltimore District with technical support from the Ordnance and Explosive Waste Mandatory Center of Expertise and Design Center at COE, U.S. Army Engineering and Support Center, Huntsville (HNC). Phase II operations included historical research of the Former Camp American University Experiment Station and Camp Leach, surveying and mapping the area, geophysical surveys of the selected properties, coordinating with the public of all activities, development of planning documents and coordinating logistical requirements for the excavation, storage, and transportation of all recovered munition items. As an element of Phase II, a geophysical survey was performed utilizing non-intrusive investigation techniques and mapping of geophysical signatures of anomalies of the surveyed properties.

The anomaly discovered at Wesley Seminary on the Former Camp American University area was determined to be possible buried chemical warfare material (CWM). The close proximity with Wesley Seminary and the American University to the anomaly site posed numerous logistical and safety problems. The no significant effect (NOSE) distance predicted for this anomaly was calculated at 329 meters for an un-contained detonation. The standard procedure is to evacuate all nonessential personnel and the public to a distance outside of the NOSE distance when suspected chemical ordnance is unearthed. The NOSE distance calculated would encompass all of Wesley Seminary, a large portion of the American University including student housing, and several residential homes in Spring Valley. This was deemed unacceptable due to its high cost and serious logistical complexity. A method to safely reduce the NOSE distance was required.

HNC was tasked to develop an engineering control solution to reduce the NOSE distance. The concept developed was simple and extremely effective. The concept is to place a vapor containment structure (VCS) over the removal site, maintain a negative pressure differential between the inside environment and the outside, and filter all air inside the structure through an HEPA and activated charcoal air filtration system. This ensures that any static release of chemical agent will be contained and filtered. Unfortunately, the suspected ordnance, the Livens Projector and the 4.7" Mark V artillery, provide a dynamic release of agent. These rounds also pose a fragmentation hazard. A complete containment of agent under these conditions is not assured. In order to determine the effectiveness of the VCS for containment of agent from a detonation of suspect munitions the concept had to be field tested.

In January of 1994, a VCS prototype program was initiated by HNC to determine the containment efficiency of the VCS.

2.0 DEVELOPMENT AND TESTING OF THE VAPOR CONTAINMENT STRUCTURE

The VCS selected for development (Figure 1) was a 14 gage corrugated steel arch manufactured building with a 5000-cfm HEPA and activated charcoal air filtration system. The factors in selection were expected ease of construction, availability, and durability in an explosive loading environment.

Southwest Research Institute (SwRI) in San Antonio, TX was selected in January 1994 to test the VCS to determine its containment efficiency. The VCS prototype was erected on the SwRI facilities in preparation for testing. The VCS was erected on a sand bag base with concrete blocks used to provide structural restraint against the predicted worst case interior loading from a detonation.

The sand bag base was used to evaluate the use of sand bags as leveling tools in the field. Since intrusive activities are discouraged before the actual removal operation, no base leveling with bulldozers or backhoe were expected. Use of sand bags is the expedient way to level the site without digging.

The first task in the evaluation of the VCS is to determine accurate detonation parameters. Analytical models used for conventional explosives do not always accurately predict the loadings for chemical ordnance. In this case both the Livens Projector and 4.7" Mark V had high ratios of chemical agent fill to explosive burster quantity. This tends to damp out the shock loads. If the agent is relatively non-combustible, the agent will quench the fireball eliminating any serious quasi-static pressure increase. Fragmentation analytical models greatly over-predict fragment velocity when dealing with liquid filled munitions. An accurate determination of the detonation parameters is necessary for both the prototype test evaluation and the field use.

2.1 Arena Tests

Arena tests were first performed on the two suspected munitions. These tests had three objectives. First, the munitions equivalent explosive weight in bare TNT must be determined based upon the side-on pressures measured. Second, the fragmentation potential for the

munition must be evaluated. Finally, the munitions effectiveness in agent dispersal must be evaluated.

2.1.1 Munition Descriptions

Actual Livens munitions were not available for use in the test program and drawings of the Livens Projector were used to fabricate full scale geometric models of the Livens munition. The model munition was fabricated using two hemispherical endcaps machined to the same thickness of the Livens munition (3/16 inch thick). These endcaps were welded to a cylindrical section having a wall thickness of 3/16" inches. One of the endcaps was designated the fill side of the munition and had a 1 inch hole drilled in the endcap and a threaded coupling welded over the hole to allow for filling the munition with simulant. The other end of the munition had the burster tube welded to it. The steel burster tube had 1.34 inch outer diameter and a 1.0 inch inner diameter. The burster extended 15 inches inside of the munition as shown in Figure 1. The end of the burster tube inside the munition was sealed to prevent the contamination of the burster charge by the chemical agent simulant. The other end of the burster tube extended out of the munition approximately 1 inch and was threaded to accept a cap which was used to seal the burster well after the explosive and detonator were placed inside the burster well. All steel components of the model Livens were constructed of A36 steel.

The Livens had a 0.16 pound TNT equivalent burster. The actual Livens was filled with the liquid form of chemical phosgene at roughly a pressure of 60 psi. The Livens function simply by the burster destroying the outer containing shell and dispersing the phosgene which upon release to atmospheric pressure vaporizes into a cloud.

Actual 4.7" Mark V munitions were also not available for the tests to be conducted. A model munition was fabricated that was simplified in order to reduce cost of fabrication while maintaining the fragmentation, overpressure, and agent dispersal characteristics of the actual munition. The burster and nose configuration of the actual munition is close to that used in the simplified munition with the case thickening at the end of the cone curvature. The majority of fragments would result from this nose section around the burster of the actual munition and the simplified munition. The tail sections of both the actual and simplified munition will break up into larger pieces with low velocity components.

The 4.7" Mark V artillery has burster explosive weight of .27 pounds of TNT. The 4.7" is also filled with liquid phosgene at 60 psi.

2.1.2 Arena Test Setup

The arena test setup was as shown in Figure 2. The munition was surrounded by four velocity screen bundles and 14 gauge steel witness plates. The velocity screen bundles were used to capture fragments and predict fragment velocity. The witness plates were used to evaluate the fragment's ability to perforate a 14-gage steel structure at close range. Two PCB pencil type pressure gauges were used to determine the side-on overpressure resulting from the detonation.

The electronic velocity screens were constructed of bundles of celotex faced by two layers of foil separated by a poster board. The foil layers functioned as an open switch in a circuit. When a fragment penetrated the screen and came in contact with both layers of foil, the circuit closes and sends a signal to the data recorder. Electronic break wires were attached to the munition so that upon detonation another signal was sent to the data recorder. With the time zero given by the break wires signals and the impact time given by the velocity screen, an estimation of fragment velocity can be made.

Another method of fragment velocity was used by evaluating the fragments using the THOR equations for depth of penetration into the celotex bundles. Given the fragment mass, presentation area relative to celotex bundle impact, and depth of penetration into the bundles, and estimation of impact velocity can be made. The limitations on this technique are that the fragment tends to roll and may not give an accurate prediction.

Two simulants were used in the arena tests, ethylene glycol and SF6. Ethylene glycol has a specific density approximate to that of liquid phosgene. SF6 has dispersal characteristics to phosgene vapor, is non-combustible, and has low detection limits. Ethylene glycol was used to determine the actual fragmentation attributes of the munition while SF6 was used to determine the effectiveness of the VCS for containment of agent.

2.1.3 Arena Test Results

The major objectives, as previously stated, were to evaluate overpressure, fragmentation, and agent dispersion from a munition detonation.

The pressures which best match the actual pressures expected from a detonation of a Livens Projector are from the model munition containing ethylene glycol as its agent simulant. This simulant best models the blast performance of the munition since it has a specific density approximate to that of the actual Livens.

The side-on pressure measured by the pencil gauges set at a horizontal distance of 4 feet from the munition was 0.93 psi. Using the computer program CONWEP, an equivalent charge weight in bare TNT for a near surface hemispherical burst is determined. This charge weight is 0.0006 pounds. This is a marked difference from the actual burster weight of 0.16 pounds and demonstrates dramatically the effects of a large liquid agent fill to charge weight ratios.

The applicable overpressures for the 4.7" Mark V result from the arena test of the ethylene glycol filled munition for the same reasons as discussed for the Livens.

The side-on pressure for the 4.7" measured by the pencil gauges set 4 feet from the munition was 4.7 psi. Using the computer program CONWEP, an equivalent charge weight in bare TNT for a near surface hemispherical burst is determined. This charge weight is 0.02 pounds. While the difference between the calculated charge weight and the actual burster weight of 0.27 pounds, there is still a significant reduction resulting from the fill material and casing. The liquid fill to charge weight ratio is less than that of the Livens and correspondingly there is less of a reduction in pressure.

As previously mentioned, the fragmentation of the munitions was evaluated in three ways. First the maximum fragment velocity was determined using the data from the velocity screens. Second the fragment velocity of individual fragments were calculated using the THOR equations based upon the fragment characteristics and depth of penetration. Finally the 14 gauge witness plates were visually inspected for fragment perforation.

The arena tests which best model the actual munitions were the ones using the ethylene glycol filled munitions. The ethylene glycol filled munitions best model the blast response of the munition since the specific weight of ethylene glycol and liquid phosgene are similar.

The model Livens had a large liquid fill to burster weight ratio and the outer shell was comparatively thin. This causes the munition to break up in a manner similar to that of pressure vessel failure. The shell remained largely in two pieces with the shell petalled back around the burster. The fragments which impacted and penetrated the velocity screens were very small and posed no threat to the 14-gage VCS structure.

The model 4.7" munition the liquid fill to charge weight ratio was significantly less than that of the Livens and this results in a failure mechanism similar to that of conventional ordnance. The shell broke up into two large tail section pieces and numerous long slender fragments from the nose section. There were some fragment perforations in the witness plates. The velocities measured by the velocity screens and calculated using the THOR equations indicated that both the tail section and the nose section fragments could perforate the VCS structure.

The total number of possible model 4.7" munition fragments which could perforate the VCS structure was calculated based upon the test results.

Chemical agent dispersion aspect of the munition detonation was evaluated solely on visual inspection. Both the model Livens and 4.7" Mark V performed up to expectations with good agent dispersal. No liquid remained with either round after detonation.

2.2 VCS Prototype Test

The testing of the VCS was simple in concept and difficult in implementation. The method of evaluation was to cover the VCS structure with a capture tent connected to a high velocity fan (Figure 3). Any simulant escaping the VCS after a detonation of a SF_6 munition was captured by the tent and the simulant dosage was measured by a continuous monitor in the annulus connecting the capture tent to the fan. There was also a monitor on the exhaust from the VCS filter system. From measurements recorded by these two monitors the effectiveness of the VCS in percent agent captured was determined.

Numerous Summa type capture devices were placed around the VCS to determine the worst leakage locations. Several devices were also placed outside the capture tent to measure the simulant dosage that was not captured by the test setup. These devices function as vacuum samplers which sample all air around them for 20 minutes. They are then sent to a laboratory to determine the total simulant dosage captured.

Blast gages were placed inside the VCS and two pencil type overpressure gauges were placed outside the VCS in front of the roll-up door.

2.2.1 Results

The VCS was tested for the model Livens munition with SF_6 fill first. The munition was detonated in a 3.0 feet deep pit simulating a removal operation. The measured efficiency of the VCS for the Livens was greater than 99.4% agent captured. The shock wave pressures measured were between 1 and 2 psi and the VCS

sustained no damage. There was no significant quasi-static pressure increase.

The 4.7" Mark V was also detonated in a 3.0 feet deep pit with shielding used to restrain the fragments. The shields were necessary due to site limitations at SwRI and were constructed so as to not inhibit simulant dispersal. The VCS structure was pre-perforated to account for expected perforation based upon the results of the arena tests. The measured efficiency of the VCS for the 4.7" Mark V was greater than 99.7% agent captured. The shock wave pressures measured were between 2 and 4 psi and the VCS sustained no damage. There was no significant quasi-static pressure increase.

3.0 FIELD DEPLOYMENT AT WESLEY SEMINARY

The VCS was deployed at the Wesley Seminary site following the completion of testing in September 1994. The site had a rough slope of around 10%. While this would not hinder performance of the VCS it was decided that the public perception of the competency of the VCS could be hampered by the structure being placed upon a slope. It was decided to level the structure using a combination of trenching and sand bags. The structure was erected by a contractor using a telescoping forklift and several laborers. There were 1/8 inch thick blast shields placed over the openings of the air system intake and exhaust. Ramps were provided at each door. The structure was restrained using cables attached to mobile home anchors. It took roughly a week and a half to construct the VCS.

3.1 Benefits From Deployment

The benefits of using the VCS at Wesley Seminary were dramatic. If suspected chemical ordnance were unearthed without protection, the surrounding community must be evacuated to distance greater than 329 meters. This corresponds to an evacuation area of 3,660,000 square feet or 340,000 square meters. The required evacuation distance for the Livens and 4.7" Mark V inside a VCS are 50 meters and 20 meters respectively. This corresponds to an evacuation area reduction of 97% for the Livens and 99% for the 4.7" Mark V. The evacuation area required using the VCS at Wesley Seminary encompassed one home only.

3.2 Field Deployment Problems and Lessons Learned

Several problems occurred during deployment.

The VCS structure was placed in a trench and on sand bags in order make it level. The soil in the trenches was not compacted and the structure tended to settle in the loose fill. This could have been avoided by use of sand bags in the trench on top of compacted soil.

The ramps used posed several problems. The ramp connection had to be flexible in order to account for uneven terrain. The ramps selected would not allow the roll-up door to be closed and the ramp surface was too slick. The ramps also tended to sink into the wet ground. A standalone ramp unit could be used which has a larger base which would help prevent settling by spreading the load out. Since the ramp is a standalone unit, it will not interfere with door operations. A lugged surface should also be used.

The manufactured structure used as the VCS shell was heavy and awkward to erect. The bolt holes did not align correctly in some cases and the access to some bolt locations was limited. These problems could be mitigated by better coordination with the manufacturer to enhance the constructability of the structure.

4.0 VCS USAGE

It is expected that the VCS tested and deployed at Wesley Seminary will be used for other removal projects. There are several issues which must be considered prior to using the VCS for a removal action.

4.1 VCS Use Parameters

The VCS can be used for other CWM removal projects. The following issues must be resolved before deployment at the site:

> Will the VCS withstand the blast pressures?
>
> Will fragmentation cause serious damage to the VCS?
>
> Can a air filtration system be provided which will provide a negative air pressure environment inside the VCS greater than the positive quasi-static pressure increase from an explosion?
>
> What is the capture efficiency for the VCS for the expected CWM item?

The VCS cannot be used if the blast pressures are above the limit for the VCS, heavy fragmentation is expected, or the quasi-static pressures are excessive. The NOSE distance for the particular deployment must be determined based upon the capture efficiency. The NOSE can be calculated using a computer program called D2PC.

HNC is aware of the need to baseline the VCS is required to facilitate its use at other sites.

4.1 VCS Baseline Testing

The prototype structure remains at the SwRI research site. HNC will be conducting baseline tests for explosive resistance and agent release on this structure this fiscal year (1996). The baseline tests include two phases.

First the structure maximum credible event (MCE) limit will be established. A succession of tests will be conducted for a number of charge weights incrementing upward until the point before yielding of the structure or roll-up door occurs. The structure will be instrumented to measure stresses and strains in several locations. It is expected that the testing will start at around 1/2 pounds of TNT and increment up 1/2 pounds at a time until near failure is reached. The charge weight for the near failure point is the MCE for the VCS.

Following these tests, Phase II will be conducted to determine the agent capture efficiency for the VCS for a series of charge weight and agent combinations. The testing will be similar to the prototype VCS efficiency test. The capture efficiency will be determined for several charge weights up to the structure charge weight limit.

Once the baseline tests are complete, the VCS can be used for any chemical munition with a charge weight less than the VCS MCE and if it meets the fragmentation limitation. The withdrawal distance will be calculated based upon the VCS capture efficiency at chemical munitions charge weight and the actual amount and type of agent fill.

5.0 VAPOR CONTAINMENT FABRIC STRUCTURE

Other vapor containment structures and devices which could be used in nonexplosive environments for capture of static releases are being used and developed. Light weight vapor containment fabric structures (VCFS) have been used for containment of static releases and future operations using these lighter structures are planned (Figure 4). Future testing of these lighter structures is anticipated. Issues to be tested include resistance to blast pressures, fragment resistance, tear resistance, and agent capture efficiency.

6.0 PARTIAL CAPTURE SYSTEM

Another CWM agent capture system is the partial capture system (PCS). The PCS is a engineering control that was developed by HNC to capture the majority of a static (nonexplosive) release of agent inside a pit or trench. The PCS uses two suction heads along side a trench or pit connected to a high-flow fan system which will generate a 35,000 cfm suction air flow rate. The PCS is shown in Figures 5,6,7, and 8. If wind screens are provided the PCS can capture close to 100% of an agent release. An air filtration system must be attached to the high-flow fan outlet. This air filtration system must have the same flow capacity (35,000 cfm) as the fans. Additional refinements to the PCS are anticipated including enlarging the shroud, testing lower flow rates, and small quantity explosive release tests.

7.0 EMERGENCY ON-SITE CWM DEMOLITION

Another use of the VCS is also be considered and analyzed.

HNC developed an on-site ordnance demolition container for use in cases in which an open or buried detonation of ordnance is not allowed. The container has been tested and validated for repetitive use for detonations of up to six (6) pounds TNT and fragmentation of 57mm artillery shells or equivalent. The container system is designed to prevent all fragments, and the majority of the blast pressures from escaping the container. An interior blast mat is used to capture the majority of fragments, preventing damage to the outer shell. The outer shell can stop all fragments from a detonation without benefit of the blast mat. The overpressures are mitigated using water bags placed around the munition prior to detonation.

HNC is analyzing the possibility of using the on-site ordnance demolition container with the VCS to provide an emergency on-site demolition process for recovered CWM (Figure 7). Initially, HNC is looking at demolition of non-explosive CWM such as chemical agent identification kits. Methods being considered include using a caustic solution in lieu of water in the water bags and/or using a 5 to 1 ratio of explosive to agent. The caustic solution may neutralize the agent, and the 5 to 1 explosive to agent ratio has been shown to combust a majority of a phosgene release in previous testing. Further analysis is ongoing and future testing is anticipated.

8.0 CONCLUSIONS

The U.S. Army Engineering and Support Center, Huntsville, Ordnance and Explosive Waste Mandatory Center of Expertise and Design Center is actively developing better and more efficient ways of containing and mitigating the effects of accidental releases of harmful chemical agents. HNC is dedicated to the utilization of the latest technologies in order to better protect the environment and the public through its Innovative Technologies Program.

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2. Vargas, L.M., Marchand, K.A., and Brewer, J.H., June 1994, "Testing of Steel Arch Confinement Structure for 4.7" Chemical Munitions Hazards," Southwest Research Institute Final Report.

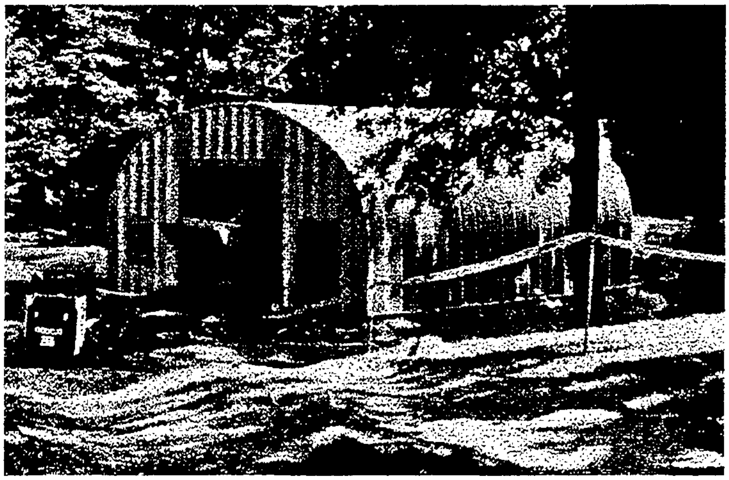

Figure 1 - VCS (Spring Valley)

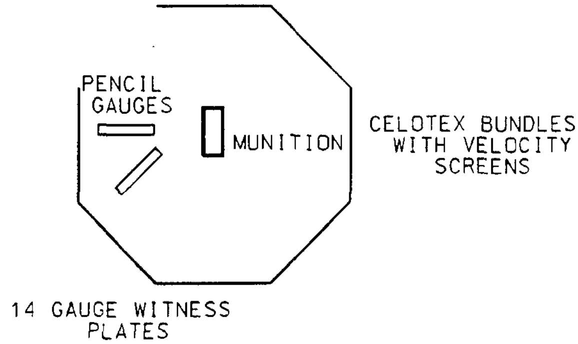

Figure 2 - Arena Test Set-up

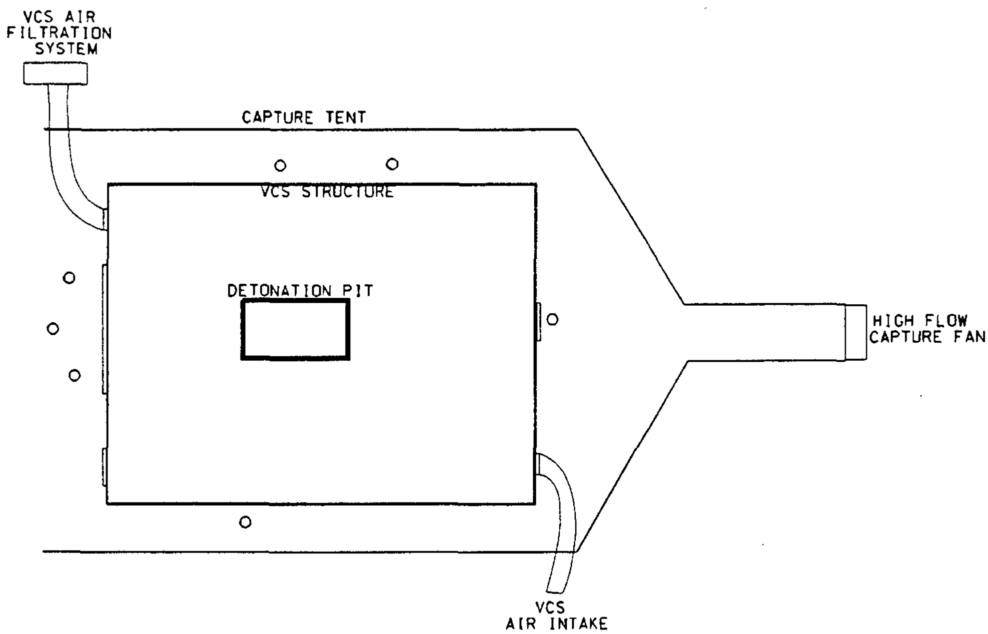

Figure 3 - Vapor Capture Test Set-up

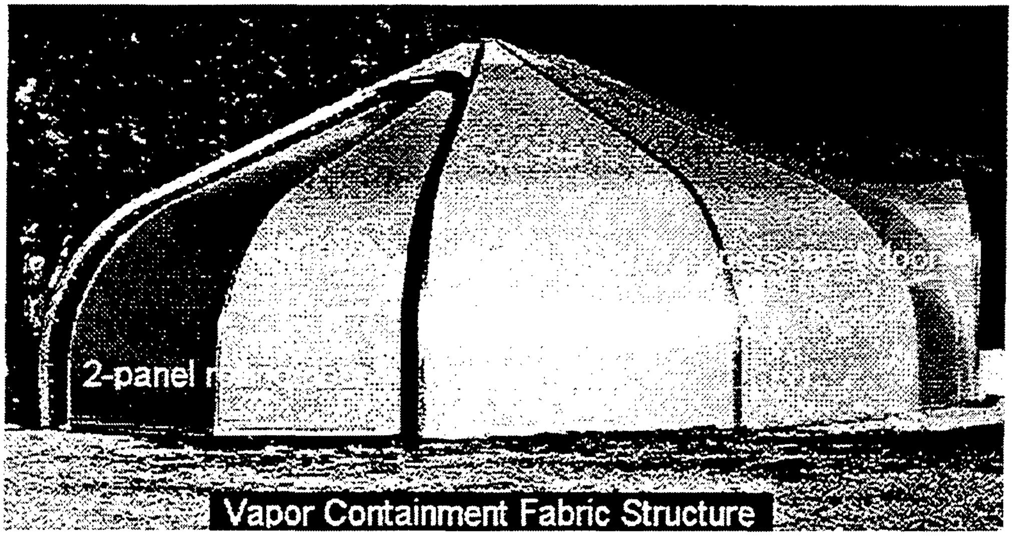

Figure 4 - Fabric VCS

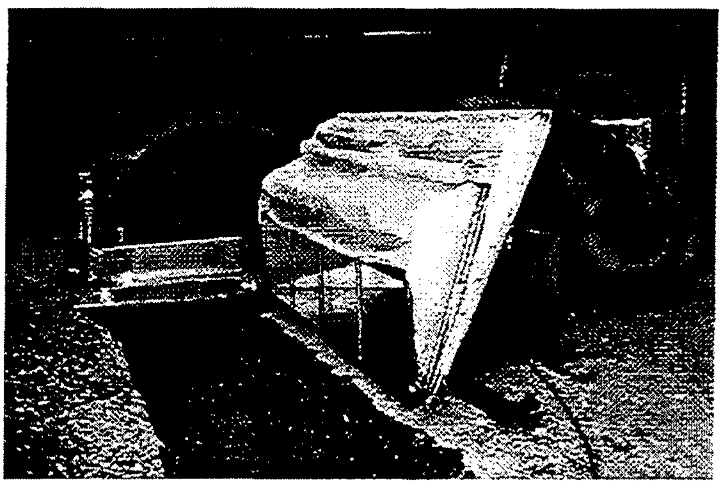

Figure 5 - PCS (Shroud Up)

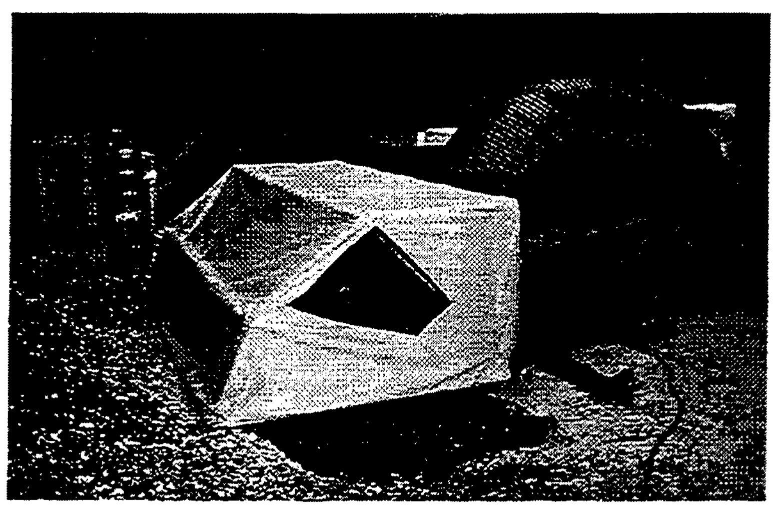

Figure 6 - PCS (Shroud Down)

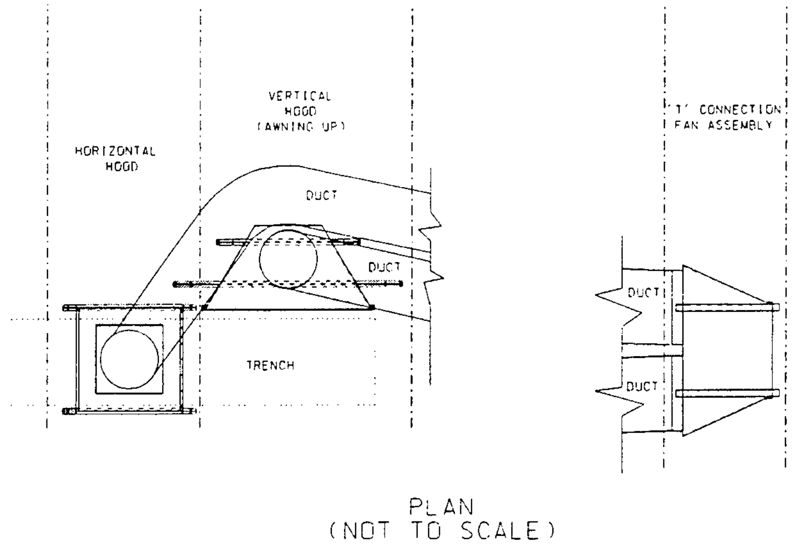

Figure 9 - PCS Set-up (Plan)

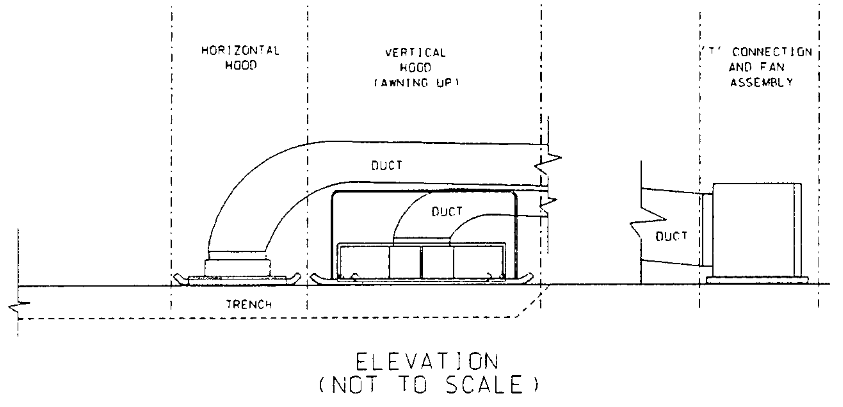

Figure 8 - PCS Set-up (Elevation)

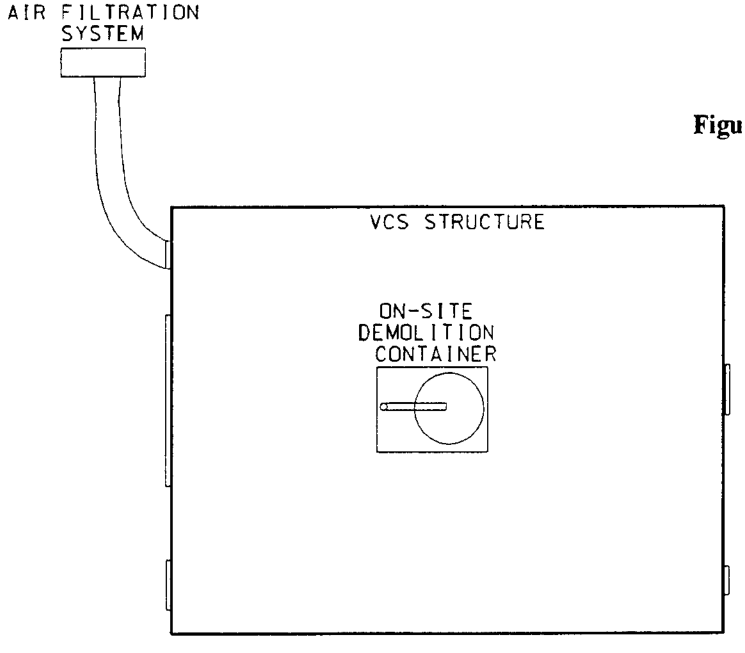

Figure 7 - Emergency On-site CWM Demolition Set-up

DETECTION, CLEARANCE AND DISPOSAL OF UNEXPLODED ORDNANCE FROM WORLD WARS IN GERMANY

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ABSTRACT

51 years after the end of the war in Germany, more than 2000 t/a of conventional warfare agents were detected, cleared and destroyed. This number has increased excessively after the German Democratic Republic had come to an end, and the systematic detection and clearance of unexploded ordnance was started in the new Federal States of Germany. The State of Brandenburg is the most concerned one, with a quantity of 500 t/a of unexploded ordnance. Unexploded ordnance includes abandoned items of military origin and parts of such items, which

- contain explosive materials or consist of explosive materials (i.e. gun cartridges, grenades, bombs, mines, etc.)
- contain chemical agents, smoke materials, fire warfare agents, pyrotechnics, and irritants.

Immediately after the end of the war, one has begun to detect/remediate and destroy the unexploded ordnance. The areas in the Baltic Sea, where ordnance was dumped, are nowadays regarded as to be the largest warfare-related contaminated sites. At the end of the Fifties, an organization structure for warfare agent detection and clearance was formed on the basis of the "Allgemeinen Kriegsfolgelastengesetzes (war indemnity). This organization is still valid in Germany. The Department of Interiors of each Federal State of Germany is responsible for the search, detection, clearance, and disposal of unexploded ordnance in view of danger prevention. Danger prevention and the existing safety requirements are the reasons, why open burning and open detonation have been regarded as to be the best techniques until 1995. From 1995 on, also the non- private plants for destruction of ammunition have to adhere to the valid environmental laws.

From the times of the First World War, the "III Reich", the Second World War and from the occupation, several hundred, not yet remediated sites with warfare-related contaminations are existing in Germany. These have to be added to the areas which have formerly or nowadays been contaminated with hazardous military waste in the old and new Federal States as well as to abandoned sites of the military industry, the German Army (Bundeswehr) and the Soviet Army. 7500 areas have until now been registered, which are contaminated with ammunition, explosives and chemical agents. The acutely dangerous points - in these cases also contaminated soil is concerned - have to be remediated from hazardous military waste/unexploded ordnance by private companies or state departments for detection/clearance and disposal of UXO. This is very difficult, since it is not possible to raise the required funds and find an optimum, cost-saving technical process for storage, disposal and remediation.

1.0 DEFINITION OF "WARFARE-RELATED CONTAMINATED SITES" AND "UNEXPLODED ORDNANCE"

The task of the companies for detection and clearance is to prevent hazardous situations during clearance of unexploded ordnance and securing of warfare-related contaminated sites.

Warfare-related contaminated sites are

- Former production sites for warfare agents and ammunition, which were used until 8th of May 1945 for research, testing, production, storage, utilization or disposal of warfare materials.
- Ammunition storage sites
- Training areas
- Detonating and open burning grounds
- Disassembly plantsTemporary and landfill sites
- Large tank plants
- War operations areas
- Areas, contaminated by own German unexploded ordnance where explosives and chemical agents,

Table 1 - Explosives and Explosives Mixtures in Germany

Code Number	Mixture	Denomination
9	30 % of No. 14 + 70 % Ammonium Nitrate	Fp 30/70
13	60 % of No. 14 + 40 % Amminium Nitrate	Fp 60/40
14	100 % Fp 02 / TNT	Fp 02
16	90 % of No. 14 + 10 % Nitropenta	
17	50 % Dinitroanisol + 35 % Aminnium nitrate + 15 % Hexogen	Amatol 40
20	53,5 % Ammonal Nitrate	Diamine
24	100 % Picric Acid	Gra.Full 88
25	80 % Hexogen + 20 % Aluminium Powder	HA 41
32	100 % Nitroglycerine Powder	
36	60 % Nitropenta + 40 % Montan Wax	
38	35 % Nitropenta + 65 % Montan Was	
42	70 % Nitropenta + 30 % of No. 14	Pentol
48	80 % Nitropenta + 20 % Aluminium Granules	Pentrit A
53	30 % TNT + 8 % Hexogen + 45,5 % Ammonium Nitrate + 8 % Calcium Nitrate + 8 % Guanidine Nitrate + 0,5 % Vultanol	Ammonit 43A
56	12 % of No. 15 + 80 % Amminium Nitrate + 4 % Saw Dust + 4 % Nitroglycerine	Donarit
57	100 % Monachite	
83	100 % Ethylenediaminenitrate	PH-Salz (Salt)
84	46 % PH-Salz (Salt) + 46 % Ammonium Nitrate + 8 % Calcium Nitrate	Sonderfüllung 84 (Special Filling 84)
88	10 % TNT + 52 % Ammonium Nitrate + 6 % Calcium Nitrate + 30 % PH-Salz (Salt) + 2 % Montan Wax	Amatol 41
95	60 % Hexogen + 40 % TNT	Hex/Tri 60 : 40
96	50 % Hexogen + 50 % TNT	Hex/Tri 50: 50
98	45 % Hexogen + 40 % TNT + 15 % Aluminium Powder	HTA 15
101	100 % Fp 02, phlegmatized with wax	
104	100 % Hexogen	
105	70 % TNT + 15 % Hexogen + 15 % Aluminium Powder	Trialen 105
109	80 % of No. 104 + 20 % Aluminium pyro polish	PMF
110	90 % Ammonium Nitrate + 4 % Aluminium pyro polish + 4 % Naphtaline + 2 % Saw Dust	Ammonal D
111	90 % Ammonium Nitrate + 9 % Carbon Dust + 1 % Aluminium	Ammonal S
112	80 % Ammonium Nitrate + 20 % TNT	Ammonal J

that were added to the warfare agents to comply with the requirements, waste and residues from production and residues from disposal of conventional and chemical UXO were handled. Unexploded ordnance is the ammunition of all weapons which were utilized on the European continent during during both World Wars. This also includes foreign ammunition. Unexploded ordnance consists of a large number of various labile, partially still working tactic systems with metal jackets and explosives. Furthermore, it has to be assumed that the quality of the explosives produced during war times does not meet the status of the science and technique of production in times of peace. Due to leaving in soil and water, their effectiveness, sensibility and handling attitude cannot be estimated. Origin, igniting mechanism as well as type and condition can not or very hardly be determined. Type and condition of unexploded ordnance are thus decisive for the technical layout of the disassembly and disposal, considering damages caused by corrosion and ensuring a safe destruction. Unexploded ordnance includes - besides the conventional warfare agents - also ammunition containing chemical agents, smoke materials, fire warfare agents and irritanting agents. Table 1 shows a list giving some explosives and mixtures used in both World Wars. Abandoned ammunition is much more dangerous than stored ammunition, since the condition of the ammunition, especially the safety mechanism, could have undergone an aging-process during the time of abandonment that cannot be determined. The metal jackets of the ammunition, which has been produced out of different materials, such as steel, aluminium, brass, copper, tin or zinc, is exposed to an inside and outside corrosion process.

Type and extent of the corrosion are determined by the water contents of the soil, the venting degree and the type of soil. The extent of corrosion is greatest in humus soils, since sulfides are formed due to the degradation of the organic soil substance. For soils in Germany, the corrosion of steel jackets is about 0,1 mm per annum. Increased temperatures and humid/warm climate lead to the blooming of phlegmatizers of the aromatic nitro compounds. The explosive material changes colour and appearance. Since the bloomings often take place in the acidic area, an additional and too strong oxidation with the surrounding material could occur. Thus, the stress and impact sensible picrate crystals will be formed. Due to lying in the soil and chemical reaction with the shell material (copper, aluminium) and other materials, the functioning of the initial explosives becomes erratic. Sand or similar materials as friction agents could also increase their sensibility.

2.0 LEGAL BASES AND ORGANISATION OF DETECTION AND CLEARANCE

Basis for the organisation of clearance and destruction of warfare agents in Germany is § 19 of the "Allgemeinen Kriegsfolgelastengesetzes (AKG)" in connection with art. 120, para. 1 of the constitutional law. According to this law, the Federal Government is responsible for the elimination of hazard sources, if these have already been established in course of the "Dritten Reich" or by any other official company. This concerns

- Warfare-related contaminated sites owned by the German Republic, if no other polluter can be determined or be made liable and

- Areas, not owned by the German Republic, where the contamination is due to UXO formerly owned by the state.

According to this law, the individual Federal States are responsible for assessment, detection, clearance and disposal of conventional and chemical warfare agents under the condition that a concrete hazard for the public safety is given. This condition is given if there exists a hazard for human health and groundwater.

This task belongs to the responsibilities of the police law or the law. Thus, the local authority for maintenance of order and safety is responsible.

This authority - the Department of the Interiors of the Federal States - has own departments for detection, clearance and disposal of warfare agents. Their responsibilities are regulated by special decrees. In most of the Federal States, only these departments for clearance are allowed to carry out the disposal. Each Federal State owns a central unexploded ordnance demilitarisation plant. The state-owned departments for clearance and disposal of UXO may place suborders to industrial contractors acc. to § 7 of the law for explosive materials. Normally, the department for clearance remediate the individual items, while the industrial companies will receive a contract for clearance of areas. The clearance of warfare-related contaminated sites will be supervised by a responsible person from the department. The state-owned company has to be informed about the acceptance of orders so that the transport and supply of the UXO can be secured.

In Germany, a working team was formed by the managers of the federal departments for detection and clearance. The task is the interdisciplinary exchange of experiences and the elaboration and update of statistical data concerning the self-detonation which contains about 40 to 50 points, i.e. accidents with ammunition in course of

construction works, excavating works, boring activities and incorrect handling.

The Federal Government of Germany pays to the individual Federal States up to 50 million Deutschmark per year. The financing depends on the budget and on the number of letal accidents and self-detonated blind shells (bombs). There cannot be seen a trend that the number of still to be detected unexploded ordnance has decreased. The activities of the industrial contractors and the departments for detection and clearance of UXO are generally limited to the clearance and disposal of UXO containing explosives as major component.

The obligation to remediate and destroy chemical agents can only be fullfilled partly, since the destruction and temporary storage in the state-owned UXO demilitarisation plants involves quite serious problems concerning construction, process technique and necessary protection by observing the required safety distances.

For their own requirements, the Bundeswehr (German Army) has facilities for clearance and disposal of chemical agents and chemical ammunition, which can be used in accordance with the Department of Interiors of Niedersachsen - in exceptionally urgent cases or as official technical assistance.

Working protection and safety are very important factors for clearance and destruction. For protection against possible effects of detonations, only the general law for safety techniques, as mentioned in the law for explosives, had been valid until the plants for disposal of UXO had obligatorily to be approved according to the Bundes-Immissionsgesetz (Federal law for immissions). The clearance has to be carried out under consideration of the "Unfallverhütungsvorschrift Nr. 13" (Accident Preventing Regulation No. 13) of the "Berufs-genossenschaft Chemie" (Professional Union for Chemistry). For the disassembly and disposal, the law for explosives and the guidelines for disassembly and disposal of ammunition (ZH 147-1) are valid.

The safe destruction of conventional ammunition can be summarized as follows:

- The explosives have to be burnt in long layers, and separated according to the type of explosive material.
- The highest allowable quantity per burn-out and burning ground has to be observed.
- Encounterings (inclusions) must be prevented.

The necessary protection and safety distances and constructions have to observed. For the clearance of warfare-related contaminated sites and of chemical agents, the guideline of the "Tiefbaugenossenschaft ZH 1/483" (= Professional Union for Civil and Underground Engineering ZH 1/483) for working in contaminated areas is valid.

Since clearance of unexploded ordnance underlies the Federal Law for Immissions, the emission limit values of the "17. Verordnung zum Bundes-Immissions-schutzgesetz" (17. Regulation to the Federal Law for Immissions) acc. to table 2 have to observed for disposal by means of open detonation, open burning and burning-out. Emission measurements of open burning have proven that the emissions of an open burning and open detonation cannot be obtained.

This has the consequence that the destruction areas of the UXO demilitarisation plants operated until now have to be closed and that new facilities for closed incineration plants with off-gas cleaning have to be built.

Table 2

Emission Limit Values according to the 17. Regulation of the Federal Immission Law

(Daily average value)

Particulate matter (dust)	10 mg/m³
Organic matter (total organic carbon)	10 mg/m³
Gaseous anorganic chlorine compounds, hydrochlore emission (HCl)	10 mg/m³
Gaseous anorganic fluor compounds, hydrofluoric acid (HF)	1 mg/m³
Sulphur oxide described as SO_2	50mg/m³
Nitric oxide described as NO_2	200 mg/m³
Carbon monoxide (CO)	50 mg/m³
Co + Ti	total 0,05 mg/m³
Hg	0,05 mg/m³
Sb + As + Pb + Cr + Co + Cu + Mn + Ni * V+ Sn	total 0,5 mg/m³
Dioxins, Furanes	0,1 mg/m³

3.0 ACTIVITIES FOR DESCTRUCTION OF WARFARE AGENTS

The activities and tasks of the departments for clearance and destruction can be summarized as follows:

- Clearance of bombs after evaluation of air photographs
- Check of building sites due to an application by the construction companies
- Systematical clearance of areas, contaminated with unexploded ordnance
- Pick up and transport of abandoned unexploded ordnance
- Disassembly and destruction of the complete cleared ammunition.

The techniques adapted by the companies/ departments for detection, clearance and destruction of warfare agents from site assessment up to the destruction are determined by the type of unexploded ordnance, the ammunition techniques and the climate conditions. Only the sequence of the individual working steps remains unchanged.

3.1 Assessment and Detection

In those Federal States which have been very much involved in the activities of war, the assessment of the site is carried out by evaluation of air photographs. For assessment of areas, Germany generally uses metal detectors, which are able to detect the exact position of ferromagnetic materials down to a depth of 10 m. Non-ferrous material, such as explosives lumps, cannot be detected, so that one has to rely on coincidental detection or has to start detailed research. The detection is carried out with teams of 2 to 6 people, who are working in a distance of 100 m between each other. Detected items remain on the place where they were found. The place of detection must not be entered before supervising personnel, the department for clearance of UXO or a representative of such a company has arrived.

3.2 Manual Clearance and Identification

This clearance is principally effected manually. The identification is made by an expert and experienced responsible blaster. The available sources are - besides experienced expert personnel - the documentation about unexploded ordnance, collection of patterns and the UXO information system KAMIS, which are all in the possession of the departments for detection and clearance of UXO. If it is assumed that chemical agents from the First World War (7,5 cm) are concerned, then the working activities for identification in case of a site remediation will increase. The outside appearance of chemical warfare agents is not very different from that of conventional ammunition. In many cases, the outside features (filling screw, color marking or engraved code) cannot be determined. By means of a gamma meter or X-rays, the technical design of the ammunition item can be checked. It can, however, only be determined whether the contents are liquid or solid. In order to identify further characteristics, heavily contaminated ammunition will be treated by means of a wet jet unit. Upon identification, also the safety of the warfare agent will be checked. If a transport cannot be made due to safety hazards, then the destruction has to be carried out at the point of detection. Bombs will be deactivated on site. For this purpose, a remote controlled deactivation facility will be used. The igniter will be detonated on the site of detection.

3.3 Clearance and Transport

The expenditures for clearance depend on the size of the site and on the type of the assumed UXO. For individual abandoned items, it is sufficient to keep transport containers available. Since chemical agents have a very aggressive attitude against metals, special containers are used, which will in case of a failure prevent the discharge of gases by increasing the internal pressure. For clearance of sites and at areas which are contaminated with chemical agents, the complete equipment consists of:

- Metal detectors
- Manual clearance and transport equipment
- Apparatus for identification
- Machine for lifting (dredging shovel with exhaust air cleaning, classification conveyors)
- Heatable working hall with air circulation and sprinkler plant
- Containers for decontamination, social and sanitary facilities, as well as for material
- Weather station, supervising operator for phosgene, video supervision
- Machine for disassembly (hacksaw, milling machine, drilling machine, apparatus for field disassembly)

At the time being, it is discussed to carry out the disposal of conventional UXO on site if the clearance of a complete area is concerned, since the clearance activities would be very cost- and personnel-intensive. Mobile plants are a further point of discussions, which consist of an assembly unit, a popping oven (as it is presented later) and a relevant pollution abatement system.

3.4 Unexploded Ordnance Demilitarization Facility

The unexploded ordnance demilitarization facility has the task to destroy UXO. The unexploded ordnance shows an indefinite condition so that it can be handled and disassembled with the lowest possible expenditure. Only a thermal disposal will be possible. UXO is disassembled or dismounted so far only that the initiating flames will ensure a complete incineration. The residual materials - mostly metallic marketable products - have then to be sold free of explosives and free of other contaminants. The incineration residues have to be disposable. The large variety of unexploded ordnance requires certain operation steps in regard to sorting, treatment, confectionning and charging of the explosives and ammunition parts to be handled. An ammunition demilitarization facility is constructed such that it can be adapted with low expenditure to the latest technique. It consists of the general technical area, the administration, and a plant part containing the equipment for disassembly and disposal:

- Storage for UXO (storage bunker for bombs, large and small calibre ammunition, fire and smoke materials, chemical agents, contaminated and explosive mixtures, high explosives and igniting agents).
- Disassembly and dismounting facility (wet jet cleaner, disassembly of igniters and cartridges, disassembly rack with sawing equipment and isolating loop).
- Disposal facilities.

3.4.1 Disassembly

Latest technique for the disassembly of unexploded ordnance is the cutting with water-cooled saws and the beating of bombs to gain the explosives in form of lumps. The disassembly of grenades by unscrewing the igniter cannot be made, since the individual components could be damaged by corrosion. Thus, the disassembly is firstly equipped for cutting the igniter with a safety distance of 10 cm. According to the safety regulations, discs, which are 1,5 to 2 times thicker than the diameter of the projectile (depending on the size of the projectile) will be obtained by the sawing process. In table 3, the relevant cutting data for selected projectile groups could be seen. The high pressure abrasive cutting did not succeed due to the required quantity of 1 kg of abrasives for 1 kg net explosive material.

Table 3
Cutting data and sawing time for selected projectile groups

Projectile Group Calibre Size	Number of Cuttings	Sawing Time (min.)
7,5 cm - Projectiles	2	8
8 cm - Projectiles	2	6
8 cm - Missile Grenade	1	6
10 cm - Projectiles	2	14
12,2 cm - Projectiles	3	15
12,8 cm - Projectiles	3	25
24 cm - Projectiles	5	60

3.4.2 Thermal Treatment of Unexploded Ordnance Under the Conditions of An Open Burning

Due to safety reasons, the open burning of abandoned unexploded ordnance has until now been regarded as to be the latest technique. According to this, UXO demilitarisation facilities were and are operated as an intermediate solution with the following disposal facilities:

- Explosives burning bunker for the open burning of loose explosives and explosives in open shells
- Popping oven up to 55 g TNT-equivalent for the detonative disposal of not disassembled small calibre ammunition or ammunition components
- Coke ovens for the burning-out of not further dismountable or other not to be initiated ammunition parts
- Burning ground for propellants
- Detonation bunker for detonation of UXO which cannot be destructed in another way.

Open burning means the self-maintained burning of loose explosives and ammunition components under normal pressure and ambient conditions. Technically, the burning is achieved by initiating the burning by a wood fire (endothermly) and by forming layers whereby the layer thickness and width depend on the relevant explosive material. The burning is determined by the specific burning characteristics of the explosive

material. This specific burning attitude will be influenced by a variety of components:

- The condition and form of the layers
- The burning conditions, such as oxygen, temperature and pressure
- The type of ignition
- The quantity to be burned

The self-maintained burning is after ignition characterized by short concentration peaks of emissions and off-heat. The composition of the emissions and the distribution of the involved reaction partners via the residues, off-gases and particle emissions depend on the burning conditions and the specific burning attitude. The emission tests up to date carried out in Germany have proven that there is just a minimum of emissions if the burning is carried out under normal pressure and ambient conditions, since the temperature of the flames in the reaction zone reaches its maximum at these oxygen contents. If the oxygen concentration decreases, then the burning will be incomplete and the concentrations in the incompletely converted reaction product will increase. These facts and the practically proven safety during burning in a wood fire and in long layers have in Germany led to a discussion about incineration systems, where the specific burning attitude under normal pressure and ambient conditions is technically maintained by means of a continuous operation. This principle under the conditions of an "open" burning with a collection and cleaning of the produced off-gases consists of a defined supply of ammunition into an open burning chamber. There, the explosive material will be converted after ignition (exotherm - cold) under ambient conditions. The required air will continuously be sucked and is homogeneously distributed by the flow conditions in the burning chamber. It is used as cooling and oxidating medium.

This plant (briefly ATEF) with a burning-annealing tunnel and a popping oven up to 200 g TNT-equivalent in parallel operation is actually started to be built in Germany for destruction of stored unexploded ordnance. The advantages of this plant concept are the result of long years experience in regard to disposal/destruction of conventional UXO. These advantages are:

- the specific burning conditions of the explosives can for each individual case be technically adjusted in the furnace
- a large variety of ammunition and materials contaminated with explosives can be destructed together (mixed lots)
- relevant capacity can be achieved
- the plant equipment is mechanically robust and operation is simple
- the expenditures for disassembly are less than for the well-known deactivation furnace.
- low cost technologies

3.4.2.1 Burning-Annealing Tunnel

The burning reactor serves principally for the self-maintained burning and is designed as a heat-insulated tunnel casing in form of a resistant building. The burning reactor is passed by the burning carts of which the technical equipment can be adjusted to the different types of ammunition and feed materials. Thus, the burning can be optimized by different insertions into the burning carts for feed of liquid, paste-like powdery and lumpy materials into the burning basins. The explosive materials are placed in a certain geometry into the burning basins in order to achieve the most uniform burning. The loaded burning cart will firstly be ignited in the ignition area. To remove the heat produced by the burning and to prevent a too high heating of the explosive material and thus a deflagration or detonation, fresh air is sucked into the burning casing by means of underpressure. After the material-specific burning, the burning cart is transported to the afterburning area in the annealing part. There, the annealing and outburning takes place in course of a total residence time of 30 minutes and at a temperature of more than 600° C. The determining factor is the product from throughput capacity specific pollutant quantity and off-heat per explosive material depending on the specific burning attitude. This is then decisive for the mechanically possible feed frequency.

3.4.2.2 Popping Oven

The popping oven serves for the controlled and continuous detonative conversion of not dismountable and dismounted items with < 200 g TNT-equivalent by means of hot air. The thermal treatment is limited to the pressure and splintering effects of the allowed TNT-equivalent at direct contact of the ammunition with the oven basin and by the geometry of the feed funnel of the elevator bucket. A hot air stream will be produced by a special hot air system and be maintained at a temperature of 600° C by an electric air heater. Just a small quantity from this hot air stream which is loaded with detonation vapours, will be sucked off. Thus, the popping oven is held under slight underpressure. The fresh air streams on top of the popping oven come via a pressure dampening container into the cooling unit of the feed area and to the baffles. The underpressure prevents a discharge of polluted gases.

After having filled the maximum quantity of items to be detonated into the popping oven pot, then the feed is stopped and the heating maintained for 16 minutes, so that the latest fed item can detonate.

Then the heating will be stopped and the lockings of the popping oven basin opened. This basin will then be lowered by means of the lifting and tilting device and be emptied without dust into a container. During the emptying process, the main part of the dust will be sucked from the popping oven by underpressure. This procedure is released by a field-switch in the feed area. After the emptying process has been finished, the popping oven basin will be lifted and the heating started.

The filled container will be transported to a cleaning station where the metal residues can be sorted. The metal residues and burning residues originated from the burning-annealing tunnel will also in this cleaning station be removed from the burning carts.

BUGS: AN AUTONOMOUS " Basic UXO Gathering System" APPROACH IN MINEFIELD COUNTERMEASURE & UXO CLEARANCE II

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ABSTRACT:

The objective of the Basic UXO Gathering System (BUGS) is to test, evaluate and demonstrate the use of distributed robotics in clearing Improved Conventional Submunitions and minefield neutralization. This paper addresses some of the pros and cons of building a small, robust and cheap robot by selecting an architecture, interface, coordination and simulation. The choice of architecture or interface is important in selecting a system that is flexible enough to operate reliably and robustly in an unknown environment.

INTRODUCTION:

The tasks of removing UneXploded Ordinance (UXO) by the Explosive Ordnance Disposal (EOD) technicians put the personnel under great risk. The risks are associated with the new technologies used in the submunitions or mines and the time factors that these objects have been subject to weather and environment that could trigger detonation at anytime. However, practice ranges and other lands that are contaminated by ordnance or mines must be cleared so they can be converted back to more beneficial use. Not only is the cost of training personnel in locating, gathering or disposing the unexploded ordnance enormous but this activity puts the EOD technician in great physical danger.

The main force behind building most robotics systems is to reduce the human presence in dangerous task areas such as UXO clean up and de-mining. The difficulties of performing complex tasks in the real world environment present a challenge for engineers in designing a fully autonomous system. Furthermore, the cost of building a single intelligent robot fully equipped with complex sensor capabilities is too high for use in UXO gathering or mine detection because of the risk associate with equipment destructions. The NAVEODTECHDIV goal is to develop a low cost, easy to use, and simple to maintain system to perform the Explosive Ordnance Disposal (EOD) mission. The BUGS concept consist of a reconnaissance platform with suitable sensors to detect and locate the submunition from a safe distance, and then using a low cost, simple Basic UXO Gatherer (BUG) to perform the Pick Up and Carry Away (PUCA) or Blow In Place (BIP) function. Once the desirable behavior of a single simple robot is obtained, the same architecture than can be distributed to all other similar platforms to create a group of robots to accomplish a practical and vital mission. It is believed the BUG system of cheap, simple robots, operating collectively to accomplish a mission, will be faster, cheaper, and easier to build then a single high cost intelligent robot. In testing the methodology and performance of the entire system approach some of the questions that will be addressed in this paper are:

a) **STRUCTURE:** How should the agent's system be structured, and interconnected?

b) **COORDINATION:** How should the agent coordinate or arbitrate its actions? Should the coordination be represented as a central coordinator or as distributed coordinate behavior?

c) **INTERFACE:** How should an agent capture mission intentions or human expertise to allow it to be easily brought into the agent's decision?

d) **PERFORMANCE:** What are the performance criteria in deciding the system approach or the architecture? Can these performance goals and metrics realistically be used for agents operating in dynamic, uncertain, and actively hostile environments?

e) **SIMULATION:** What role can simulation technology play in developing and comparing systems to each other?

STRUCTURE:

The choice of monolithic, subsumptive or multi-layered structural architecture of the robot depends on both the designer and the task to be executed by the agent. The designer needs to understand the operation or task requirement of the agent before choosing its architecture. It is often possible for a monolithic architecture to do the same job as any two/three/four level architecture, by selecting a faster processor or running the processor until it is saturated. In this case, this would cause some performance issues and additional work for the programmer when building a complex tasking or behavior problem.

The BUG's task in its mission requires maneuvering, avoiding obstacles, locating, and picking up target objects. Since there are a number of tasks that could slow down or cause conflict within a monolithic structure, it was decided that it is better to design the robot control using a multi-layer, parallel subsumptive structure. The coexistence of modular task decomposition and hierarchical arbitration gives the system an advantage in manageability and ease of modification.

In the hardware interface, excessive communications within the same structure can slow down the system as a whole. Centralized hardware/software control makes the system less adaptable to changing circumstances and can lead to complex control problems. We emphasize independent control of each autonomous agent to operate within its local module of the overall system, where higher modules manage the lower modules based on status report. The modular communication structure operates independently until there is a need for communication with higher or adjacent modules to keep the traffic under control. This makes the system more robust in communications by its physical connectivity. The advantages of modular structure include flexibility in manageability and incremental testability of hardware, and understandability and reusability of modules.

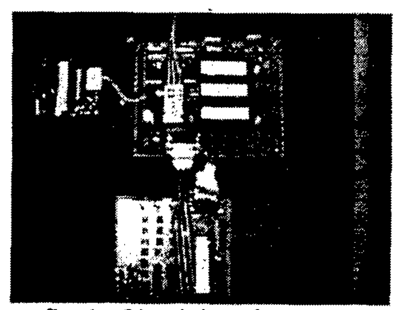
fig. 1 : Circuit interface

Whereas software behavioral coordination of a centralized control causes more of a burden on the skills of the programmer, modular programming tends to be easier. The software executing each of the various layers is completely independent and different layers do not interfere with one another. Since the BUG's response is based on various asynchronous external stimuli, such as navigation communication or environmental data, specific modular programs can operate on each stimulus or command independently. In this way, each specific modular function of the robot is capable

of reacting to the unknown terrain in real-time. Likewise, the specific coordination of the overall behavior can still be performed by its central coordinator to achieve its objective. Also, the modular software architecture allows us a platform in which behaviors are easily debugged and the reliability of robotics tasking can be tested.

Therefore, hardware and software should be completely modular and independent, to achieve complex tasks. In this way, long-term maintenance problem will be more manageable, and the agent's level of robustness will be increased. Moreover, there will be no disruption or modification of the existing structure or functionality of the agent when new capabilities need to be added.

COORDINATION:

The task of the robot determines the system coordination required. There is often a trade-off depending on the particular robot used or task performed. For example, a robot running randomly without purpose versus a robot which has a mission with defined tasks of navigation, obstacle avoidance, detection, manipulation and others. The designer is guided by task dependence in choosing one method over another.

When the robot's goals are executing more than a sequence of reactive motions behaviors, the robot's skill belongs in the level of higher intelligence. The higher intelligence robot requires a different coordination compared to the simple robot. The intelligent agents might have to accommodate a number of simultaneous complex tasks such as planning, navigating, tracking an object, grasping, real-time interacting with the terrain, or accepting guidance from a human supervisor. For many applications the designer has chosen a hierarchical control architecture. In this architecture, the goal is originated from the highest control level and flows down to the lower control levels or actuators until the objective is achieved as planned. However, one soon finds that such an architecture is not robust in dealing with a large number of information that arise simultaneously. The centralized coordinator needs to be flexible and should not control the robot's actuators directly or manage tracking and navigating by itself. Instead, the coordinator should provide indirect control by selecting among alternate functional modules.

On the other hand, distributed control module will redistribute the work load and release the hierarchy structure from the rigid system arrangement. The robustness and increase in performance is a result of independent modules able to execute accordingly from their sensor input. However, when the environment is unpredictable and conflicting commands are issued, a simple subsumptive modular architecture may not be able to arbitrate appropriate conflicting commands in order to "reach its goal."

Running either of these hierarchical or modular structures above independently is not ideal. The monolithic central structure is cumbersome and not robust or sensitive to real-time variations. The simple modular architecture is robust but does not have a central coordinator that is capable of making decisions that are not immediately obvious. Therefore, using a combination of simple subsumptive modules with some hierarchical central control to prioritize its decisions is necessary to achieve the agents' mission objective. Independent subsumptive modules generate behavior in response to real-time input from sensors allowing the system to be more flexible than central planning alone; while the central arbitrator maintains longer term goals or knowledge that can coordinate the lower subsumptive levels to keep the mission objective on track. The BUG architecture needs both centralized coordination, internally and externally, for multi-tasking, and decentralized

subsumptive structure to provide speed of reaction, flexibility and robustness.

INTERFACES:

Depending on the nature and complexity of the agent's task, the human/agent interaction may be required. Currently the BUGS system requires some type of human/agent interface to bring mission intentions to the agent for execution. It would be beneficial to have “natural human” language capability when there is frequent human and machine interaction. However, for a simple autonomous tasking robot such as the BUG, natural language is not needed. A non-natural language is more preferable because communication in a natural language will increase the complexity of the agent's system and is a poor substitute for real-time processing.

The current interface of push-button panels or joystick commands is sufficient for simple task agent. For example, the work on the BUG shows that at times one needs to give an X, Y heading or position commands, or to teleoperate the robot. Teleoperation has been implemented so that the user viewing a video image may specify the robot path by using a joystick, or by typing simple keystroke commands. This will help the agent to identify its goals, priorities, places, states, situations or status relating to the tasks, and thus help the agent in making decisions as it progresses towards its goals, or when a sub-goal is no longer applicable.

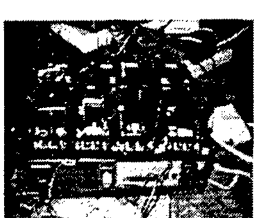
fig. 2: Video Input

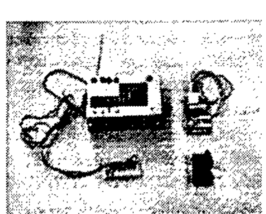
fig. 3: Remote Control

A human can serve as a control module in a hierarchical architecture of an intelligent agent. The human can intervene or execute certain controls to communicate to the agent. The robot can manage without human interaction; however when there is a need for human decision, a human will make it. For example, when the robot fails to achieve the user's purpose, the operator can override control of the robot and keep the agent away from dangers that would be unknown to the robot.

PERFORMANCE:

It is difficult to create a realistic benchmark to measure the performance of a system, either by its parts or its entirety, especially, when comparing two agents that have different controls, architectures, physiologies, approaches, knowledge or skills. Most people measure the performance of a system by its speed, cost, failure rate, or flexibility, but in actuality, the final performance measurement is subjective. How should one weight Reliability or Survivability versus Time or Cost in completing a task? If any part of the system is inoperative in the real world or slow down the system as a whole, it will totally invalidate the system evaluation. Unless the entire system is in perfect operating condition and operating as expected, there is no validity in the system performance. Even a robust behavior system dealing with the dynamic or complex part of the real world will have problems and make mistakes. There is always the possibility that some part of the system might break down due to temperature variation or electrical / mechanical problems. To make matters worse, the performance goals are associated with a group of agents or the system as a whole, not with a single agent.

Even though it is difficult to come up with an objective performance measure for a group of robots operating in the ever changing real world environment, one however, can generalize a “good-average” subjective evaluation by taking into account performance measures from various angles such as system

architecture or the percentage of the accomplished task. A generalized basis for measuring the performance of a group of agent's would be "the successful rate of the agent group is equal to the average success of each individual agent performance". This general performance criteria approach should ideally grade the entire system as a whole and not specifically on each part of the agent. The BUGS project performance will be judged on the basis of the observable performance of the group as a whole through some external and internal criteria.

Externally:

1) Percent of clearance or accuracy of task performed.
2) False target acquisition.
3) Complexity of the system.
4) Time taken to complete the mission in a given environment.
5) Total system cost for a single or multiple agents used in accomplishing the task.

Internally :

1) Is the system structure complex or simple?
2) Is the system hardware/ software expensive?
3) Is the system easy to build and/or manage?
4) Is system maintenance easy?
5) How much energy is consumed by the agent?
6) How efficient is its coordination planning?
7) How much communication is required to accomplish the task?
8) How much computational resource is required for the mission?
9) Repeatability, Reliability and Survivability ?
10) and others

The best way to evaluate the system is by running it in many realistic environments with a wide range of conditions so that the agent can successfully perform its tasks and/or fail.

fig. 4: BUGs

SIMULATION:

Simulation is not a substitute for the real world. Only robots operating in the real world terrain can provide the reliable data and results. There are many different environments that the simulation can not be characterized exactly or accurately. Likewise, it is difficult to build a "standard" simulation to compare the performance of different system approaches to the same application. All contractors are attempting to solve the same problems; however, their system approach, response, complexity or trade-offs are different. It requires extensive work for the programmer to integrate 4 or 5 different packages of simulation into one system. On the other hand, while real world testing is always better, it is time consuming and expensive.

Direct ground testing requires time and experience of the developers to tell where the optimal tradeoff point is. Depending on its tasks, real robots can damage themselves, their surroundings, other equipments or possibly people. Real robots often malfunction due to temperature change, break down mechanically or electrically, or exhaust their battery power. From this perspective, especially for hazardous missions or big projects, simulation is important both for safety and financial reasons. In the case of BUGS, simulation will be used as a rapid prototype statistical analysis tool and as a demonstration tool.

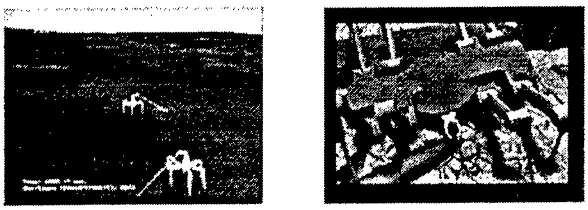

fig. 5 & 6: Simulation

The Naval Postgraduate School is building a simulation that includes a world scale model of the US Marine Corps, Air Ground Combat Center, Twenty Nine Palms, CA. terrain and a variety of robots that have the "same" functionality or characteristics as a real robot. Since the study of agent group behaviors is an emerging field, this simulation is a useful tool for studying the interaction and cooperation between a large number of agents in the real world. This simulation would solve the difficulties of implementing actual real world testing or analyzing a large number of agents in a complex world. In addition, the simulation can provide the developer with a general understanding of the total system characteristics through a large number of simulations of diverse situations. The repeatability of the simulation can provide the designer with insight into the interaction of the agent's behaviors and its environment and provides the operator with historical data records on each simulation for further analysis. The simulation will be used during the entire life of the project, to support continuous changes and to validate ideas for future improvement in a safe environment. This will simplify the developers' tasks in term of time, space, accessibility and costs over the long run.

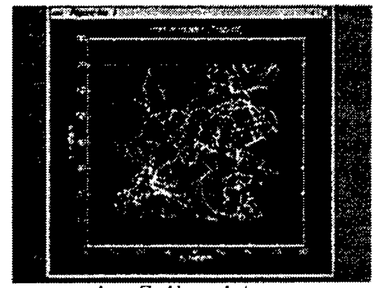

fig. 7: Simulation

SUMMARY:

This paper discussed studies in some of the key issues and approaches in building a robot for a specific mission and task. We are designing and testing the methodology in a simple robot that might be capable of expanding into a multi-robot system. We believe the subsumptive behavior control is simple and robust enough in its hardware and software structure, that these simple robots can interact in a complex and unpredictable world. A demonstration of the single robot's approach in UXO clearance and/or mine field neutralization by Draper Lab., Foster Miller Inc., IS Robotic Inc., K2T Inc., and NAVEODTECHDIV will be performed in July 1996 at NAVEODTECHDIV. We believe the demonstration of a single agent can tell us something about the capability of higher level behavior of the group in performing a mission. The future work area of group behavior robot in performing a mission is interesting and challenging. While no promise can be made, we believe that if we implement a system that is adaptive and robust in hardware and software, then the cooperative behavior of robot groups will allow us to perform practical missions in real world environments.

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CEG SAFE EXCAVATION TECHNOLOGY APPLIED TO UXO SITE REMEDIATION

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Concept Engineering Group, Inc. (CEG) has been involved in the design and construction of safe excavation technology equipment over the last several years. In an urban area, underground excavation is difficult, costly, and subject to danger from accidents involving buried utilities. Even though the location of known buried utilities should be identified and marked prior to excavation, for example through the use of the many State One Call agencies, accidents continue to happen due to incorrect drawings, location error, line misidentification, operator error, or just plain neglect. Each issue of Underground Focus, a magazine dedicated to underground construction, compiles a list of the numerous excavation accidents across the U.S. involving buried electric, gas, water, or telecommunication lines in the preceding time period. For example, the January / February, 1994, issue cites a report of some 610 damage incidents in Connecticut alone over a year period to September, 1993. In addition to the direct property and, sadly, human loss of life, the consequential damages can be huge due to a accident. For example, a cut to an AT&T buried, transcontinental telephone cable costs approximately $1.5 million per hour. Machines like bucket-wheel trenchers, ladder-trenchers, chain-trenchers, cable-plows, or rippers, which have very high production rates, cannot be used in an urban area because their damage potential is far too great. Even backhoes or hydraulic excavators, the most commonly used machines for urban excavating, are significantly slowed in production because of the time and extra care required to maneuver around existing utilities or other buried substructures. These machines, despite the care with which they might be used by a skilled operator, still have hard cutting edges and can cause significant damage. Many governmental and industrial locations are beginning to require only hand digging in an area with a suspected buried utility. Hand digging is of course slow, fatiguing, and costly in terms of both direct manpower and indirect cost of the now idle excavating equipment

When the buried object is unexploded ordnance (UXO) rather than an underground utility, the excavation problems cited above are exacerbated. It is unlikely that any engineering plan exists with as-designed or as-built locations indicated. UXO are discrete bodies of many varying shapes, sizes, and orientations as opposed to utility lines that are generally horizontal and run for substantial lengths in a given direction. UXO are located at random depths while most utilities, except for sewers, are relatively close to the surface. Most significantly, utility lines are designed primarily to deliver an item, be it electricity, gas, or information, from place to place and become dangerous only if significantly disrupted; while UXO by its very design is inherently dangerous. Putting a man in the hole to guide the backhoe operator may be common practice in the utility industry, but is highly unlikely or impossible when excavating around UXO.

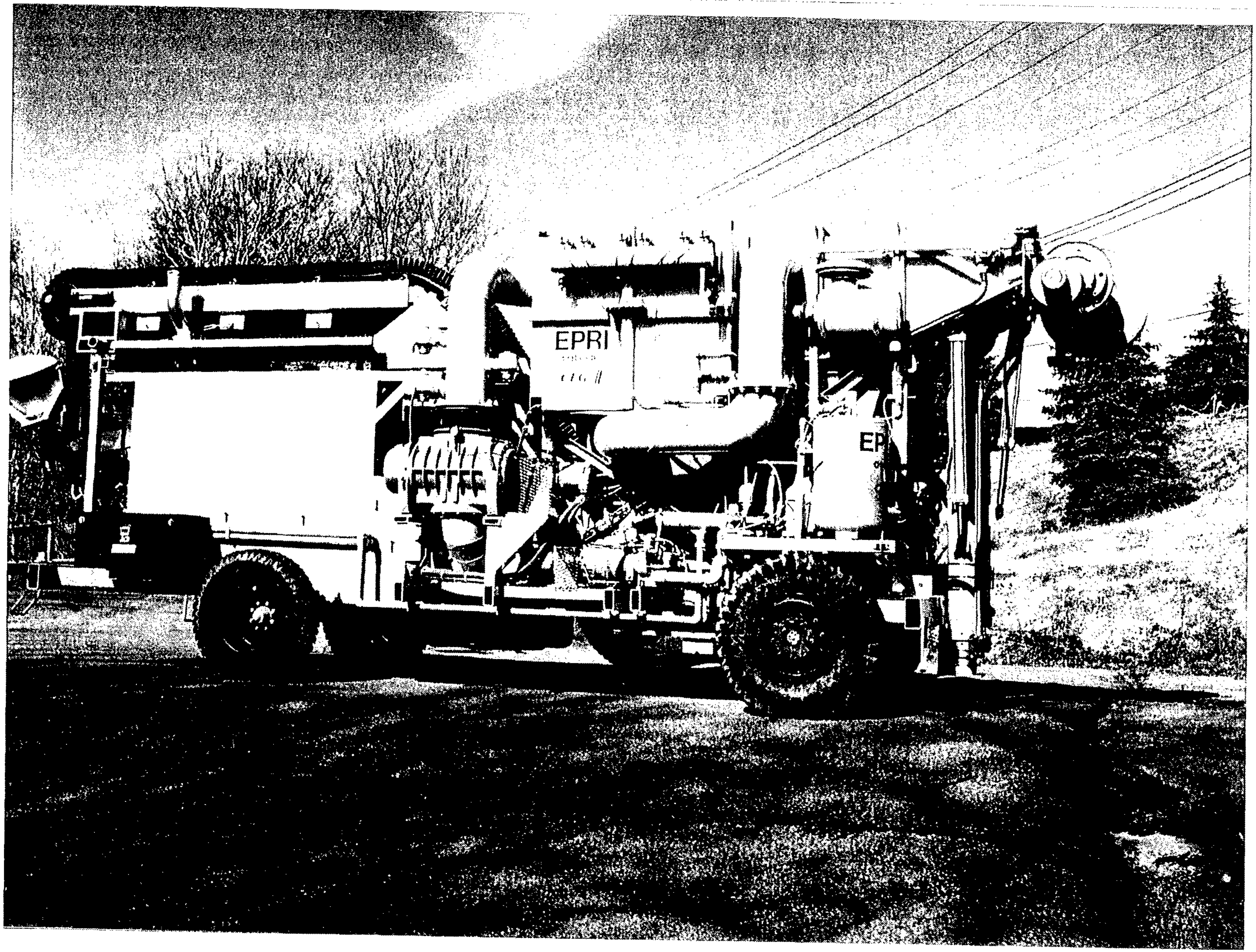
Safe Excavation

For all of the above reasons, the technology of safe excavation that CEG has been developing for the utility industry has significant advantages when applied to the remediation of UXO. This technology uses a combination of supersonic jets of air and high flow, pneumatic vacuum transport to dislodge and remove soil. The supersonic jets of air are extremely effective at penetrating most types of soil, but are harmless to non porous buried objects. The pneumatic transfer system has several unique features which allow soil, which is not the traditionally easily vacuumed material, to be handled effectively. These technologies, applicable where the need is to excavate precisely, safely, and efficiently, are distinct in several important ways.

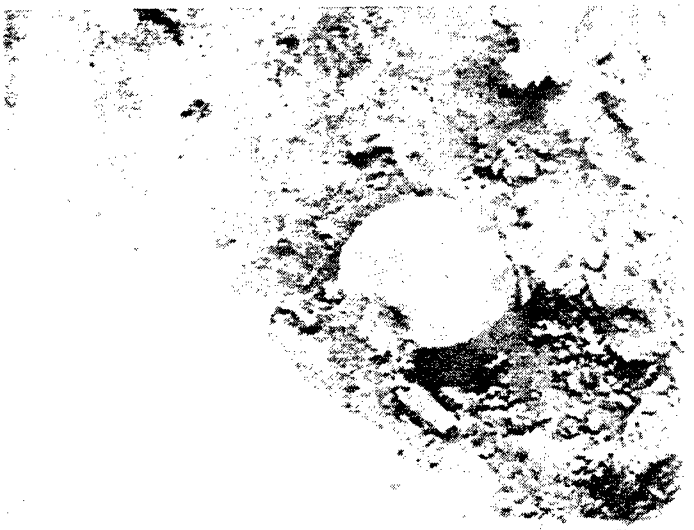
Supersonic Air Jets

Supersonic jets of air are advantageous for precise, safe excavation because:

- Unlike the hard cutting edges of blades, buckets, shovels, picks, or digging bars, have only the high speed air of the jet to contact the soil;
- Effectively penetrate and dislodge most types of soil, but are harmless to non-porous items like buried pipes or cables;
- Are two to three times faster than hand excavation and can excavate rocky types of soils where a shovel cannot be used;



VIEW OF "SOFT TRENCHER" DESIGNED & CONSTRUCTED BY CONCEPT ENGINEERING GROUP, INC.
FOR THE ELECTRIC POWER RESEARCH INSTITUTE UNDER SUBCONTRACT TO BATTELLE COLUMBUS



VIEWS OF TWO 175 MM HOWIZTER SHELLS AND ONE 155 MM SHELL EXCAVATED AT JPG SEPTEMBER 1995. ONE VIEW OF 12 CHEMICAL GLASS VIALS EXCAVATED FOR HUNTSVILLE CORPS OF ENGINEERS.

- Can be sized for different air flow rates depending on the excavation rate required;
- Deliver at a minimum twice the momentum force per unit area to the soil than a conventional "air lance;"
- Have been built to operate on compressed air as high as 250 psig, where the higher pressure "sharpens" the jet for harder soils;
- Can be used in multiples for larger excavations;
- Unlike water jets, introduce no liquid into the excavation which increases the volume of spoil for disposal or that could freeze during winter operations.

Pneumatic Vacuum Transport

Pneumatic vacuum transport naturally matches supersonic air jet excavation for a number of reasons. Like the supersonic air jets, only the suction air stream contacts the soil. The high speed jets of air effectively break up the soil into fractional inch particle sizes which are readily transported by the vacuum. When used concurrently, the jets overcome the traditional problem in suction systems of initially removing the material from the surface. The vacuum system, importantly, continuously removes the dislodged material away from the working face allowing the jets to constantly contact new material. In addition a vacuum system:

- Can remove material from a small diameter, deep excavation (pot hole) where a hand shovel or a backhoe bucket cannot;
- Pulls dust at the excavation face into the system;
- Can be filtered to various degrees depending on the material being excavated and the site regulations;
- Can be made in various sizes to match the soil excavation rate;
- Can remove other material, such as water, from the excavation;
- Has been made in sizes from approximately 200 to 4,000 acfm at up to a vacuum pressure of 16" Hg.

The excavation and vacuum transport of soil has its own unique set of characteristics. Soil types vary widely in grain size, particle shape, packing, moisture content, grading, plasticity, organic matter content, etc. Soils, in general, are not the free flowing material most conventionally moved by pneumatic transport. Special care must be taken in the design of the vacuum transport system to avoid the persistent problem of cohesive material clogging. This is especially true in the case of remote excavation where a man cannot be readily sent in to clear a clog. CEG has designed its pneumatic vacuum transport system to eliminate clogging in the transport system, a problem which conventional industrial vacuum systems are not designed to overcome.

Soft Trencher

CEG designed and constructed the Soft Trencher to demonstrate the principles of safe excavation. The Soft Trencher is a prototype device designed to safely excavate utility trenches without harming nearby, existing, buried utility lines.

The project was funded by the Electric Power Research Institute (EPRI) and assisted by Battelle Research Labs - Columbus. The design parameters were to construct a device which could excavate a trench 6 feet wide and 10 feet deep at a nominal excavation rate of 15 cubic feet per minute (photo, page 2) using safe excavation technology. The result was a self-propelled, rubber-tired vehicle machine utilizing CEG technology with supersonic jets of air for excavation and a vacuum system for soil removal. The unit elevates the soil via a conveyer and chute for discharge directly into a truck or along side the vehicle. The Soft Trencher weighs 34,000 pounds, is 27 feet long, 102 inches wide, and 11 feet 6 inches high. It is transportable on a low boy trailer without placarding. However, it is a test bed and considerably larger than a mature commercial design.

JPG Demonstration with the Soft Trencher

Recognizing the benefits of applying its safe excavation technology to UXO remediation, CEG proposed to PRC, Inc. to demonstrate the technology at Jefferson Proving Ground during the summer of 1995 under the UXO Detection & Remediation Technology Demonstration Program. Although not originally designed for such a use, the Soft Trencher was chosen as the best configuration to accomplish such a task.

Twelve excavations were performed with relative ease, with targets as deep as nine feet being exposed. The supersonic airjets successfully disturbed the soil with which they came in contact, and the vacuum transport system removed the loosened debris without encountering problems (photos, page 3). Only in the initial excavation at each site, where high grass and weeds were present, did the intake hood tend to plug. This was caused by the straw like grass acting as a filter mat to trap the excavated soil, allowing it to ball up due to lower air velocity at hood entrance compared to the higher velocity in the smaller cross sectional area of the transport tube. This condition has been solved in newer CEG safe excavation equipment designs. The complete report of

excavations by CEG's safe excavation technology, will be contained in the U.S. Army Environmental Center's report of the Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase II), when issued.

Dedicated UXO Remediation Unit

A unit designed specifically for UXO remediation at live sites will incorporates a number of additional or changed features over the commercial sized unit which has been designed by CEG for utility applications. The operator is located at a remote location rather than on or adjacent to the unit. The control of the unit is via remote radio in place of the current hard wired unit. Operator vision is supplied by television cameras mounted on the unit. Transducers are used to remotely read important machine operating parameters such as engine speed, system vacuum, air pressure, fuel supply, etc. For predominately off-road use, the unit is track mounted.

Digging Assembly

The digging assembly of the dedicated UXO remediation unit is shown in more detail in Fig. 1. In this version, the safe excavation digging assembly is actually mounted to an existing macro excavator boom section. The digging assembly consists of an excavating head, extendible soil vacuum tube, material separator, and discharge device. Soil surrounding the UXO is loosened safely via the action of the supersonic air jets. The loosened material is then drawn into the excavation head suction tube by the air flow created by the support system vacuum pump. The supersonic air jets work synergistically with the suction tube by aerating the material, and, hence, making it easier to remove by vacuum. Both systems are non-contacting to the UXO. The excavated material is transported pneumatically up the suction tube. In the material separator, the vacuumed material drops out of the airstream via directional changes and an order of magnitude reduction in the transport air velocity. A proprietary designed vertical rotary valve continually discharges material from the material separator via a chute into either the macro excavator bucket or to the ground adjacent to the excavation. The excavation head, vacuum tube, and chute is stored in a retracted position while the macro excavator is digging conventionally.

The excavating head incorporates multiple CEG designed supersonic air jet nozzles inclined at a slight angle toward the axis of the suction tube. The excavating head is covered with a resilient material, such as urethane, to cushion any incidental contact with the UXO. Compressed air is supplied via an air hose to a manifold which in turn feeds the supersonic nozzles. A spring return reel maintains tension on the air hose keeping it taught and helping to counterbalance the weight of the excavation head and lower vacuum tube.

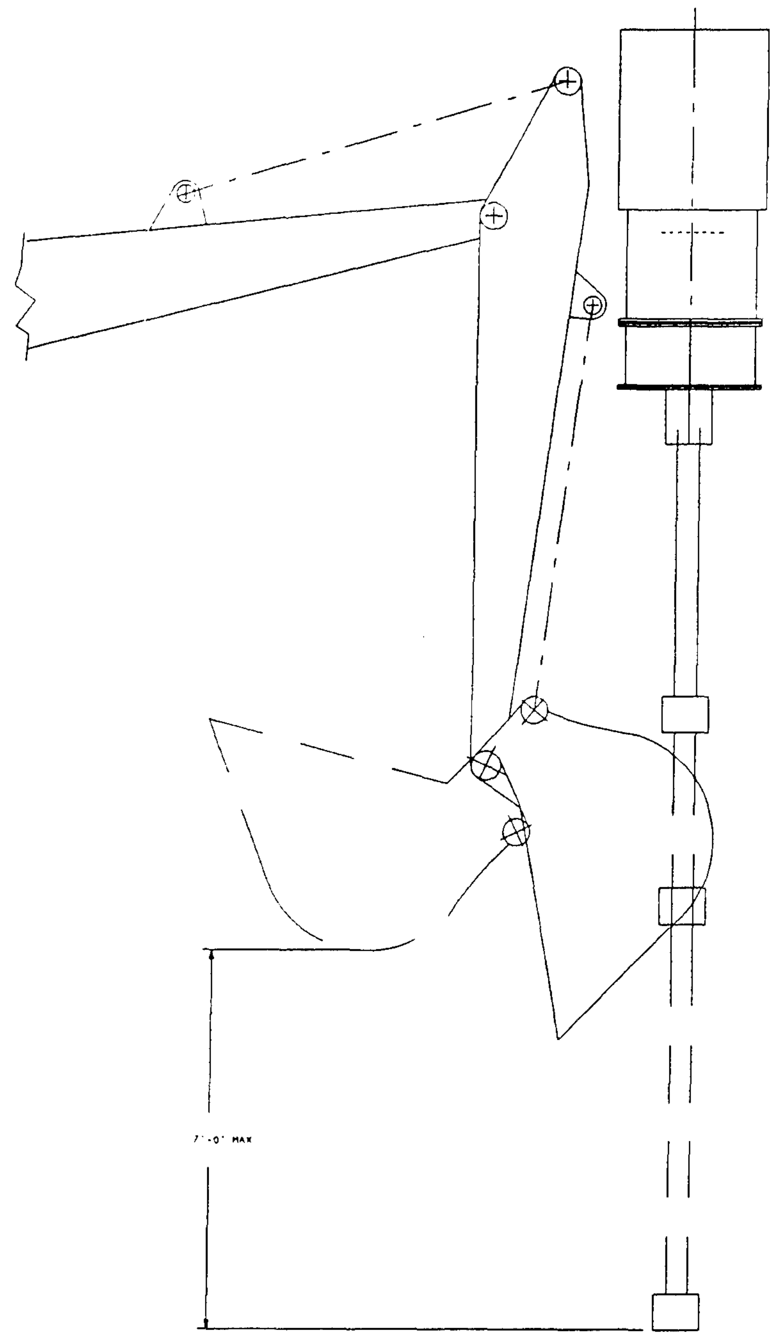
The excavating head is located on the end of a two-sectioned, telescoping vacuum tube assembly. The tubes are made of a light weight, non metallic material, such as glass fiber epoxy. These materials have shown good life characteristics in pneumatic vacuum transport of material, such as coal and rock overburden, in previous systems constructed by CEG personnel. The tubes are sized to have a sliding fit between then. Although there are several possibilities for controlling the vertical motion of the excavation head, the unit is balanced to ensure that large forces could not be exerted on the UXO. The vacuum tube is connected to the material separator with a compliant joint to give some limited rotational motion. In the case that the tube would be along side and inadvertently moved toward the UXO, this would prevent large sideways forces from being generated. Aside from the independent vacuum tube extend and retract motions, the excavation head will be maneuvered by the macro excavator using the motions of its dipper stick and boom.

The material separator is constructed of carbon steel. As stated above, all of the excavated material is removed from the air stream via air direction and magnitude changes, with final filtration performed by cartridge filters. the material separator is a flow through system, rather than a conventional storage hopper as with most other vacuum systems. A hydraulically driven vertical rotary valve discharges the excavated material continuously. A small amount of the excess hydraulic capability of the macro excavator supplies the boom extension/retraction function.

The digging assembly is attached to the macro dipper stick in a manner to make it easy and convenient to mount and demount. All of the air, vacuum, hydraulic, and electric lines have easily detachable connections.

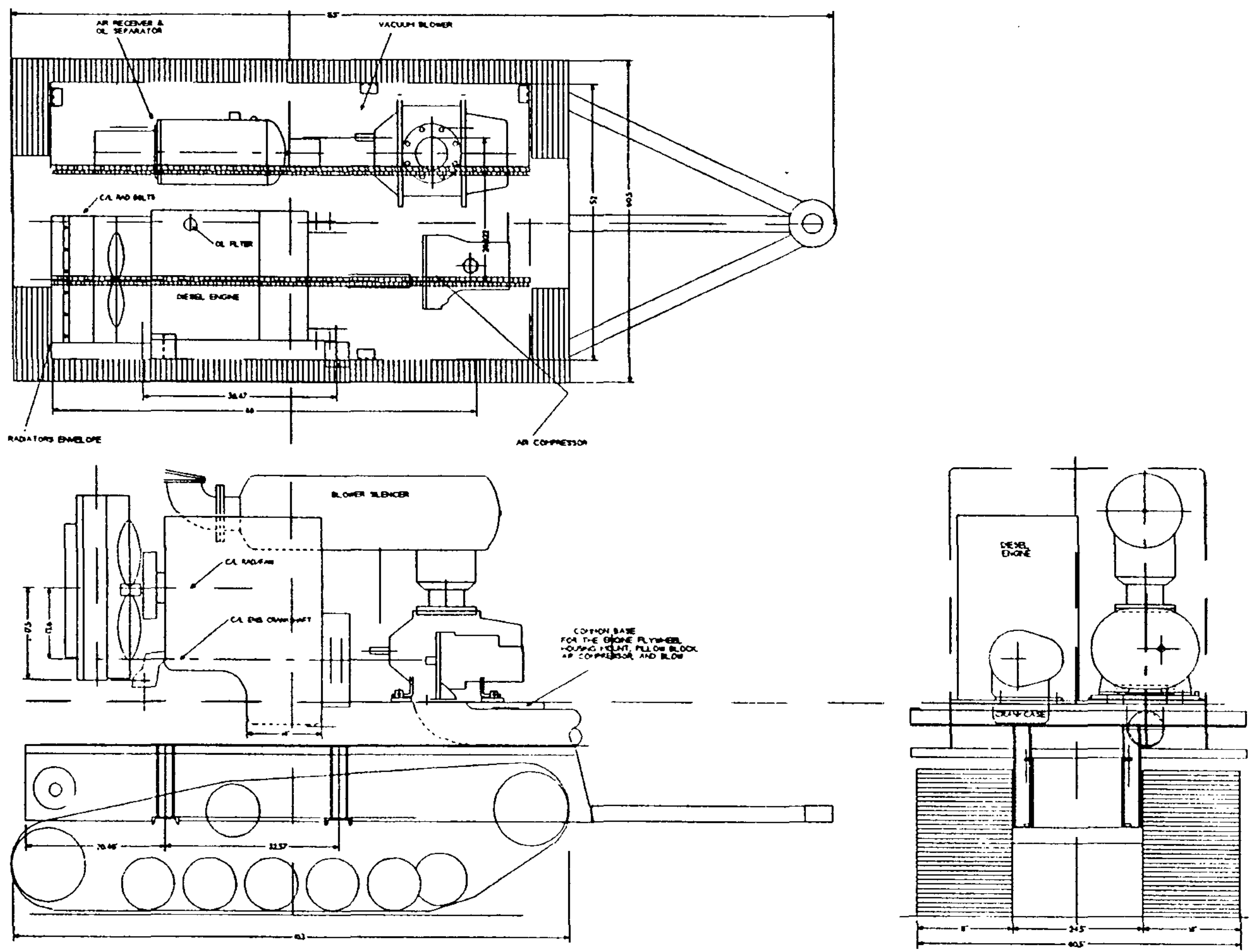
Support Unit and Connections

The digging assembly will be connected to a track mounted support unit as shown in Fig. 2. The support unit is un-powered and towed behind the macro excavator. The support unit contains the diesel engine, fuel tank, engine radiator, air compressor, air receiver, compressor radiator, vacuum pump, silencer, secondary separator, filter assembly, and control panel. The connections to the digger assembly include the compressed air feed line, vacuum return line, and electrical control cable. To be deployed along the macro dipper stick and boom of the excavator, the feed air and return vacuum lines are flexible hose or a combination of rigid pipe along the members with flexible hose at the boom joints. Standard controls and gauges for the engine, air compressor, and vacuum pump are provided on a panel mounted on the side of



CEG ROTARY MATERIAL SEPARATOR ATTACHED TO MACRO EXCAVATOR DIPPER STICK W/EXTENDABLE BOOM AND EXCAVATING HEAD

FIG. 1



CEG TRACKED EQUIPMENT TRAILER CONTAINING ENGINE, VACUUM PUMP AND AIR COMPRESSOR TO BE TOWED BY MACRO EXCAVATOR

FIG. 2

the support unit. Certain functions, such as suction tube extend and supersonic air jet on and off, are controlled from the same remote control as the macro excavator remote controls. The support unit is enclosed with a sheet metal shell with noise dampening material and access doors for normal component service.

Conclusion

The technology of safe excavation that CEG has been developing for the utility industry has significant advantages when applied to the remediation of UXO. Its combination of supersonic jets of air and high flow, pneumatic vacuum is extremely effective at penetrating most types of soil, but is harmless to non porous buried objects. This advantage allows for the uncovering of such objects without accidental detonation.

In process is the design of a unitized, self-powered, remotely controlled UXO remediator that will allow for effective operation by personnel completely removed from the target area. Such "safe excavation" can allow the UXO problem to be safely and economically neutralized.

COST-EFFECTIVE APPROACHES TO SUCCESSFUL REMEDIATION OF UNEXPLODED ORDNANCE (UXO) AT THE IDAHO NATIONAL ENGINEERING LABORATORY (INEL)

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ABSTRACT

Unexploded ordnance (UXO) and explosively contaminated soils were remediated at the Idaho National Engineering Laboratory (INEL). A Geographical Information System (GIS) was used to map areas of contamination and a Global Positioning System (GPS) was used to identify the location of ordnance explosive waste (OEW). Using these systems has improved the accuracy of the data collected. A central demolition site was used instead of the traditional method of detonating unexploded ordnance in place. Field screening of explosive contaminated soils was performed instead of using a more expensive laboratory analysis. In addition, an Air Force remote excavator was used to remediate potentially sensitized ordnance disposal pits in a cooperative technical demonstration arrangement with the Department of Defense (DoD) and the Department of Energy (DOE). The use of these methods and technologies has resulted in an enhanced remediation process and significant cost savings. The next phase of ordnance work at the INEL will involve using a computer-based site statistical sampling model for UXO estimation entitled SiteStats. This model will eliminate the need for labor-intensive field searches to estimate ordnance concentrations.

PAPER

Before the inception of the Idaho National Engineering Laboratory (INEL), military activities such as aerial bombing practice, naval artillery testing, explosive storage bunker testing, and ordnance disposal took place on a large portion of what is now the INEL. As a result of these past activities associated with the former Naval Proving Ground (NPG), numerous unexploded ordnance (UXO) devices have been discovered by INEL personnel. In addition to UXO and ordnance explosive waste (OEW), explosive agents such as TNT and RDX, released during partial detonation during NPG tests, have contaminated soils at the INEL. This paper will describe how: (a) UXO has been remediated effectively and in a cost-effective manner, (b) technologies have been used to enhance cleanup, and (c) to save money sampling explosive contaminated soils.

Over the past 3 years, UXO and explosively contaminated soils have been removed from the INEL. Lessons have been learned on appropriate approaches to take to effectively and in a cost-effective manner remediate OEW. While the cost of remediating ordnance from former military installations continues to rise, efforts are being made at the INEL to reduce these costs using innovative technologies.

Beginning in 1993, work began to remediate ordnance and explosive contaminated soils at six INEL locations. This work was completed the same year. The specific mission of this action was to locate, identify, detonate, and dispose of UXO and associated shrapnel and to characterize, remove, and incinerate soils contaminated with explosive residues.

The first phase of the ordnance removal was to set up search lanes in each area to sweep for ordnance. Five-foot lanes were established by placing metal posts and running string to each point. A visual search was made first for UXO/OEW and debris on the surface. Each potential ordnance item was flagged by explosive ordnance disposal (EOD) technicians. This search was followed by a magnetometer search to check for subsurface anomalies to a 2-foot depth. On the second search, any additional items were marked. Each flagged anomaly was investigated to determine if UXO existed. Located UXO was collected and if determined to be safe, was transported to a central blast area for destruction.

Following the clearance of an area, a quality survey of the lanes cleared was performed. If any ordnance items were discovered during the quality check, the EOD team would reclear the lanes while in the area. This ensured that a thorough clearance was performed and saved project costs.

Historical U.S. Department of Defense (DoD) EOD publications were used to positively identify ordnance in the

field. Some of these publications include: Bombs for Aircraft (TM 9-1980, 1944); General Ammunition Technical Manual (TM 9-1900, 1942); and U.S. Explosive Ordnance (NAVSEA OP 1664, 1947). Since ordnance deposited by the military during World War (WW)-II is outdated, the newer DoD publications usually do not identify the older ordnance. These historical publications assisted with identifying ordnance type, filler, and fusing. This reduces the expense of blowing up inert and nonhazardous ordnance in place. Another benefit of using these publications, eliminates the necessity of sending pictures, drawings, dimensions, and other features of the ordnance to the EOD Technical Center for identification. Processing this information through the EOD Technical Center would slow field work and cause additional project expense.

Cost savings have been realized by transporting ordnance to a central disposal area. This eliminated the need to clear areas around ordnance that would be normally blown up in the field. Clearing areas around ordnance to prevent fire danger is time-consuming and labor-intensive. Also, if each item discovered in the field is blown-in-place, considerably more explosives will be used and each detonation introduces risk. Decreasing the number of explosive detonations decreases risk associated with each disposal. Additional time and money would also be spent filling in craters and reseeding areas if ordnance was blown-in-place.

During the EOD search efforts to locate UXO, locations of soil contaminated with explosive compounds were marked. Locations with pieces of explosive compounds or stained soil present were flagged by EOD teams for sampling and the level of soil contamination was identified using field screening methods. A field laboratory was set up to conduct the sample analysis. The Jenkins Method[1] was used to perform the onsite field screening for explosive contaminated soil. This approach proved to be much less expensive than traditional laboratory sample analysis. The field screening cost per sample was $25, where the EPA 3380 Method for analysis averages $600 per sample. An estimated $297,000 was saved by using the field screening method. Ten percent of the samples were sent to an offsite laboratory for the full EPA 3380 Method analysis for verification purposes. The verification samples indicated the field screening sampling to be accurate.[2] Future samples of explosive contaminated soils will use the field screening methods. The INEL has worked with the U. S. Army Corps of Engineers (Corps) in testing and improving the Jenkins field screening methods[1,3] originally developed by the Corps.

After the soils were characterized for concentrations of explosive materials, the decision was made to remediate 186 cubic yards of soil. The soil was excavated, containerized, shipped offsite, and incinerated. The cost to incinerate the soils was $1,000 per cubic yard.[4] The current preferred method for remediation of explosive contaminated soils has changed to bioremediation. Bioremediation of explosive contaminated soils has been estimated at between 200–$400 per cubic yard.[3] The INEL is exploring ways to begin bioremediation of explosive contaminated soils. This new approach will realize substantial cost savings compared to past incineration of explosive soils.

A second ordnance removal action began in 1994 and was completed in 1995. This activity included the removal of ordnance from 90 acres from the Twin Buttes Bombing Range and 40 acres and six disposal pits at the Naval Ordnance Disposal Area (NODA).

Collecting information to identify the location, type, and disposition of ordnance is an important part of ordnance removal projects. In the past, ordnance information was manually collected and location information estimated. During the ordnance removal action in 1995, use of a Geographical Information System (GIS) to map areas of ordnance concentrations and a Global Positioning System (GPS) to identify locations of OEW has aided and enhanced the remediation process. Using these systems has improved the accuracy and quality of the information collected. Cost savings have been realized by eliminating the need to manually input field data. The field data collected can now be electronically transmitted to the GIS. The information collected will assist in future assessments of UXO at the INEL and provide a baseline for projecting further cleanup needs.

During cleanup of the NODA area, a potentially sensitive ordnance disposal pit was identified. To mitigate the potential hazards of this area, it was determined that a remote operation was necessary in this area. Costs to bring in a remote excavator were estimated at $200,000. An Air Force remote excavator (Track Catapiller 325) from Tyndall Air Force Base was selected, which was part of a previously scheduled joint demonstration project between the U.S. Air Force and the U.S. Department of Energy (DOE). The excavation of the potentially sensitive pit was included as part of the technology demonstration project. As a result of these unique activities, sites at the INEL were successfully remediated of UXO/OEW. Continued remediation will be performed in a cooperative arrangement with the DOE, DoD, and the Corps, who all work toward cost reductions for ordnance removal.

The next phase of ordnance work at the INEL will be to assess the overall levels of both ordnance contamination and the volume of explosive contaminated soils. As part of this assessment, a computer-based site statistical sampling model for UXO estimation will be used. The software entitled

SiteStats, a methodology developed by the Corps, will be used at the INEL. This tool will reduce the number of labor-intensive field searches for estimating ordnance concentrations. SiteStats will allow a minimal number of ordnance investigations, which will result in cost savings.

Innovative and efficient ordnance removal techniques will save taxpayers' money. By using new technologies, the cleanup of ordnance can be enhanced. Such techniques as field sampling for explosive contaminated soils versus traditionally more expensive laboratory analysis, electronic collection of field information, cooperative demonstration projects, and bioremediation of explosive soils will greatly improve and make ordnance removal projects much more cost-effective. The INEL has developed an integrated ordnance remediation approach the can be applied at other DOE/DoD sites.

It is important to promote cost-effective methods especially during these times of Government downsizing and reduced budgets. There remains a number of former defense sites that will require ordnance removal and soil remediation. Sharing information among those organizations responsible for ordnance removal will result in substantial cost savings.

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PHASE II CONTROLLED SITE UNEXPLODED ORDNANCE ADVANCED TECHNOLOGY DEMONSTRATIONS

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ABSTRACT

The objective of the Phase I and II Advanced Technology Demonstration (ATD) projects is to identify and evaluate off-the-shelf and innovative technologies for unexploded ordnance (UXO) detection, identification, and remediation; establish a technology performance baseline; and define the current state-of-the-art of UXO technology.

During Phase II, fifteen UXO detection systems and two remediation systems were demonstrated from May through September 1995. Detection system technologies included eight magnetometer systems, seven electromagnetic induction systems, and five ground-penetrating radar (GPR); five companies utilized a multi-sensor approach. Of the detection systems, six were man-portable, two were vehicle-towed, four were combined man-portable and vehicle-towed (multi-modal), and three were airborne.

This paper summarizes the measured performance results from the Phase II demonstrations with respect to detection, localization, and classification, by sensor type. Operational capabilities and limitations of the various systems are also discussed briefly.

BACKGROUND

The U.S. Congress has recognized the need for UXO clearance technology development and demonstration. In fiscal year 1993, the U.S. Army Environmental Center's (USAEC) efforts for demonstrating, evaluating, and enhancing UXO clearance technology were greatly expanded to address a congressional mandate for demonstrating and evaluating the performance of commercially available and government enhanced systems for UXO clearance. In fiscal year 1994, USAEC created a controlled test site containing inert ordnance at Jefferson Proving Ground (JPG). A series of Phase I demonstrations were conducted to establish a baseline for achievable UXO detection and remediation system performance. Congress appropriated additional funding in fiscal year 1995 to continue with Phase II controlled site activities. The objective of the Phase I and II ATD projects is to identify and evaluate off-the-shelf and innovative technologies for UXO detection, identification, and remediation; establish a technology performance baseline; and define the current state-of-the-art of UXO technology.

DISCUSSION OF PHASE II OBJECTIVES, PROCESS, AND DEMONSTRATIONS

USAEC and the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) selected UXO clearance technology vendors to participate at the controlled ATD site established at JPG, a U.S. Army installation recently closed in Madison, Indiana. To evaluate the effectiveness of systems in locating and excavating buried UXO, a 120-acre test site was prepared at JPG. Inert ordnance, nonordnance, and debris were buried at precisely defined but unpublished depths and orientations that are representative of

TABLE 1
DEMONSTRATED DETECTION TECHNOLOGIES

Demonstrator	Transport				Sensor System		
	Ground		Aerial				
	Vehicle-Towed	Man-Portable	Rotary-Wing	Fixed-Wing	Magnetometer	EM	GPR
Aerodat Inc.			✔		✔		
Airborne Environmental Surveys, Inc.			✔				✔
Australian Defence Industries, Pty. Ltd.		✔			✔	✔	
Bristol Aerospace Ltd.	✔					✔	
Coleman Research Corporation	✔	✔				✔	✔
Geo-Centers, Inc.	✔	✔			✔	✔	
Geometrics, Inc. [1]	✔	✔			✔		✔
Geophex Ltd.		✔			✔	✔	
GeoPotential		✔				✔	
Kaman Sciences Corporation	✔						✔
Parsons Engineering Science, Inc.		✔				✔	
Polestar Technologies, Inc.		✔			✔		
Scintrex, Inc.		✔			✔		
SRI International			✔				✔
Vallon GmbH	✔	✔			✔		

[1] Geometrics's GPR system was fielded, but results were not included for analysis

UXO-contaminated areas. In order to protect data integrity, ordnance placement was different for Phase I and Phase II activities. Types of ordnance range form mines less than 5 inches in diameter to 2,000-pound bombs. After a series of demonstrations, technology demonstrator data were compared to previously defined "target" locations in order to establish a baseline for system performance. Moreover, demonstration results are used to improve the technologies in order to achieve increasingly accurate and cost-effective systems.

During Phase II, fifteen UXO detection systems and two remediation systems were demonstrated from May through September 1995. Detection system technologies included eight magnetometer systems, seven electromagnetic induction systems, and five GPR; five companies utilized a multi-sensor approach. Of the detection systems, six were man-portable, two were vehicle-towed, four were combined man-portable and vehicle-towed (multi-modal), and three were airborne. Table 1 summarizes the detection technologies and transport systems demonstrated at the controlled site. Both remediation systems were excavators. This report summarizes the operational perfomace of both detection and remediation systems based on field oversight and their measured performance based on data analysis.

MEASURED PERFORMANCE RESULTS

Table 2 summarizes demonstrator performance with respect to detection, localization, and classification. Several conclusions can be drawn from data analysis of the demonstration results. The best performance for the probability of detection of ordnance (P_D) was demonstrated by Parson's conductivity system and Geometrics' magnetometer system. Both of these demonstrators employed advanced data processing, which may account for their higher P_D value. Demonstrators employing ground penetrating radar evidenced poor detection capabilities. Systems employing a combination of magnetometer and conductivity sensors had a narrow range of P_D values (0.65 - 0.72) that were fairly high (Table 2). The P_D values for these demonstrators is likely due to two factors: (1) collection of redundant data sets and (2) collection of additional information by the second sensor type. All of the airborne demonstrators showed poor detection capabilities, regardless of sensor type employed. False alarm rates (FAR) for the Phase II demonstrators ranged from 0.9 to 225.9 false alarms per hectare, differing greatly between the various systems. Although the GPR systems had the lowest FAR values, their detection capabilities (P_D values) were equally low, outweighing the FAR results. The next lowest FAR was achieved by a magnetometer system at 2.3, however, the highest FAR was also produced by a magnetometer system at 225.9. There appears to be no direct relationship between FAR and P_D, although both are important parameters in determining the best technology for UXO remediation.

Figure 1 is a plot of P_D versus the probability of false alarm (P_{FA}) for the demonstrators. This plot shows the demonstrators with the better detection performance in the upper left corner and those with poorer performance in the lower right corner. Both of the highest performers shown in this figure, Parsons and Geometrics, employed advanced data processing, which may have contributed to their good performance.

Figure 2 illustrates the localization capability of the various sensor types. This figure depicts the mean horizontal positions and mean vertical depth errors in meters. In general, magnetometer sensors and a combination of magnetometer and electromagnetic induction sensors proved to have the best capability in localization both horizontally and vertically.

With respect to classification by type (ordnance or nonordnance), demonstrator performance in determining ordnance objects was significantly better than their respective ability in determining nonordnance items. In face, few demonstrators showed any capability to discriminate nonordnance (see Figure 3). The best performance was shown by Geophex with a probability of 0.23 of correctly classify nonordnance. For demonstrator size estimates, about two-thirds of their probabilities of classification were greater than 0.5. Demonstrators were collectively better at estimating the size of the emplaced ordnance than they were at determining the class of target detected. Demonstrators exhibiting a capability to classify were more successful at correctly classifying bombs and projectiles. None of the demonstrators exhibited the ability to correctly classify clusters even though many of them detected clusters.

FIELD PERFORMANCE RESULTS

The capabilities and limitations of the various detection systems were influenced by the transportation mode utilized, the terrain at the demonstration areas, and the weather conditions. Man-portable systems were more durable and were able to access the entire site successfully, but these systems were limited by the speed

TABLE 2
SUMMARY OF PERFORMANCE RESULTS

Sensor Type	Demonstrator	Detection			Localization	
		P_D (Ord)	FAR (#/hectare)	P_{random}	Horizontal (Radial) (m)	Vertical (|Depth|) (m)
Magnetometer (MAG)	Geometrics	0.83	26.7	0.04	0.65	0.62
	ADI (MAG)	0.63	31.7	0.04	0.74	0.68
	Vallon	0.57	225.9	0.25	0.83	0.98
	Scintrex	0.50	45.3	0.06	0.94	0.87
	Aerodat	0.02	2.3	0.02	2.29	2.07
Electromagnetic	Parsons	0.85	32.5	0.05	0.79	0.72
	Bristol	0.62	38.2	0.05	1.04	0.97
	GeoPotential	0.11	12.0	0.02	1.30	0.80
Ground-Penetrating Radar (GPR)	AES	0.05	0.9	0.01	2.76	0.99
	SRI	0.02	2.6	0.02	3.49	2.42
	Kaman	0.00	4.2	0.01	NA[a]	NA
Magnetometer & Electromagnetic (EM)	Geo-Centers	0.72	84.0	0.10	0.81	0.88
	Geophex	0.71	19.7	0.03	0.91	0.62
	ADI (MAG + EM)	0.65	34.5	0.05	0.74	0.68
EM & GPR	Coleman	0.29	15.9	0.02	1.41	1.00

Note: NA Not applicable

TABLE 2 (CONTINUED)
SUMMARY OF PERFORMANCE RESULTS

Sensor Type	Demonstrator	Type		Size			Class				Survey Site
		Ordnance	Nonordnance	Large	Medium	Small	Bombs	Projectiles	Mortars	Clusters	
Magnetometer	Geometrics[1,2]	1.00	0.00	0.74	0.54	0.80	NA	NA	NA	NA	16A
	ADI (MAG)	0.75	0.11	0.65	0.57	0.96	0.77	0.42	0.35	0.00	16B
	Vallon[2]	NA	NA	0.17	0.88	0.38	0.33	0.00	0.00	0.00	16B
	Scintrex	0.95	0.00	0.50	1.00	0.25	0.75	0.40	0.33	NA	16A
	Aerodat[2]	NA	NA	NA	NA	NA	NA	NA	NA	NA	32
Electromagnetic (EM)	Parsons	0.78	0.10	0.16	0.75	0.23	0.12	0.57	0.25	0.00	16A
	Bristol[2]	NA	NA	NA	NA	NA	NA	NA	NA	NA	16A
	GeoPotential[1]	1.00	0.00	0.00	0.50	0.33	0.50	0.60	0.33	NA	16A
Ground-Penetrating Radar (GPR)	AES	0.89	NA	0.75	0.00	0.33	1.00	1.00	0.00	NA	32
	SRI[2]	NA	NA	NA	NA	NA	NA	NA	NA	NA	32
	Kaman[2]	NA	NA	NA	NA	NA	NA	NA	NA	NA	16A
Magnetometer & Electromagnetic	Geo-Centers[1]	1.00	0.00	0.67	0.80	0.86	0.93	0.76	0.00	0.00	16B
	Geophex[2]	0.96	0.23	0.88	0.38	0.43	NA	NA	NA	NA	16A
	ADI (MAG &	0.73	0.11	0.65	0.53	0.92	0.77	0.38	0.35	0.00	16B
EM & GPR	Coleman[1]	1.00	0.00	0.14	0.25	0.92	0.33	0.87	0.00	0.00	16B

Notes: NA Not applicable
[1] Demonstrator reported all target declarations as "ordnance"
[2] Demonstrator did not provide type, size, and class information for declarations or listed as "unknown"

and stamina of the field equipment operator. Vehicle-towed systems covered the site quickly but were often subject to breakdowns that caused time-consuming delays. Multi-modal (man-portable and vehicle-towed) systems were able to take advantage of the strengths of each system while overcoming single system weaknesses. Airborne systems, while yielding the best coverage and speed, proved to have very low detection, localization, and classification capabilities.

Both remediation systems experienced difficulties with operating remotely and had numerous breakdowns; one demonstrator experienced system failure so severe that it necessitated equipment shutdown and work stoppage. Although the systems were slow (due in part to the breakdowns), both systems exhibited the ability to successfully expose buried ordnance.

RELEVANCE OF THE UXO ATD PROJECT

Currently available site characterization and remediation tools are not adequate to effectively and efficiently respond to the UXO problem. As it becomes necessary to address the growing number of UXO sites worldwide, advanced technologies will be needed to assist in the site restoration and risk reduction process. The UXO ATD project constitutes an important first step in a series of testing and evaluation projects to help meet this need. The lessons learned from the first two phases of the project have enabled the ATD project team to identify key issues and program areas that must be addressed to meet the needs of DoD:

•P_D values must be improved while a reduction in FAR is realized.

•FAR values must be reduced through more sophisticated processing and better discrimination techniques.

•Classification capabilities must be improved to make remediation more cost-effective.

•Advanced data processing and data fusion from multi-sensor platforms must be investigated.

•Site survey speed must be increased without compromising detection capability.

•To be useful, airborne systems or other large area survey technologies must be developed or improved.

•Systems need to be evaluated under varying environmental and topographic conditions.

•Systems need to be evaluated according to specific performance capabilities and strengths.

As future phases of the UXO ATD program are implemented, these eight areas will be explored in detail. Several military installations slated for BRAC activities or with UXO remediation needs have expressed interest in expanding the project to include clearance technologies for particular sites. The ATD project can supply environmental restoration managers at BRAC and other UXO-contaminated sites with meaningful data regarding the types of clearance technologies that may be applicable, cost-effective, or efficient at particular sites. As more BRAC sites are returned to the public, the need for a project evaluating UXO clearance technologies will become even greater.

REFERENCES

U.S. Army Environmental Center. 1995. "Phase II Controlled Site Unexploded Ordnance Advanced Technology Demonstration (Preliminary Draft)." April.

FIGURE 1 PROBABILITY OF DETECTION VERSUS PROBABILITY OF FALSE ALARM

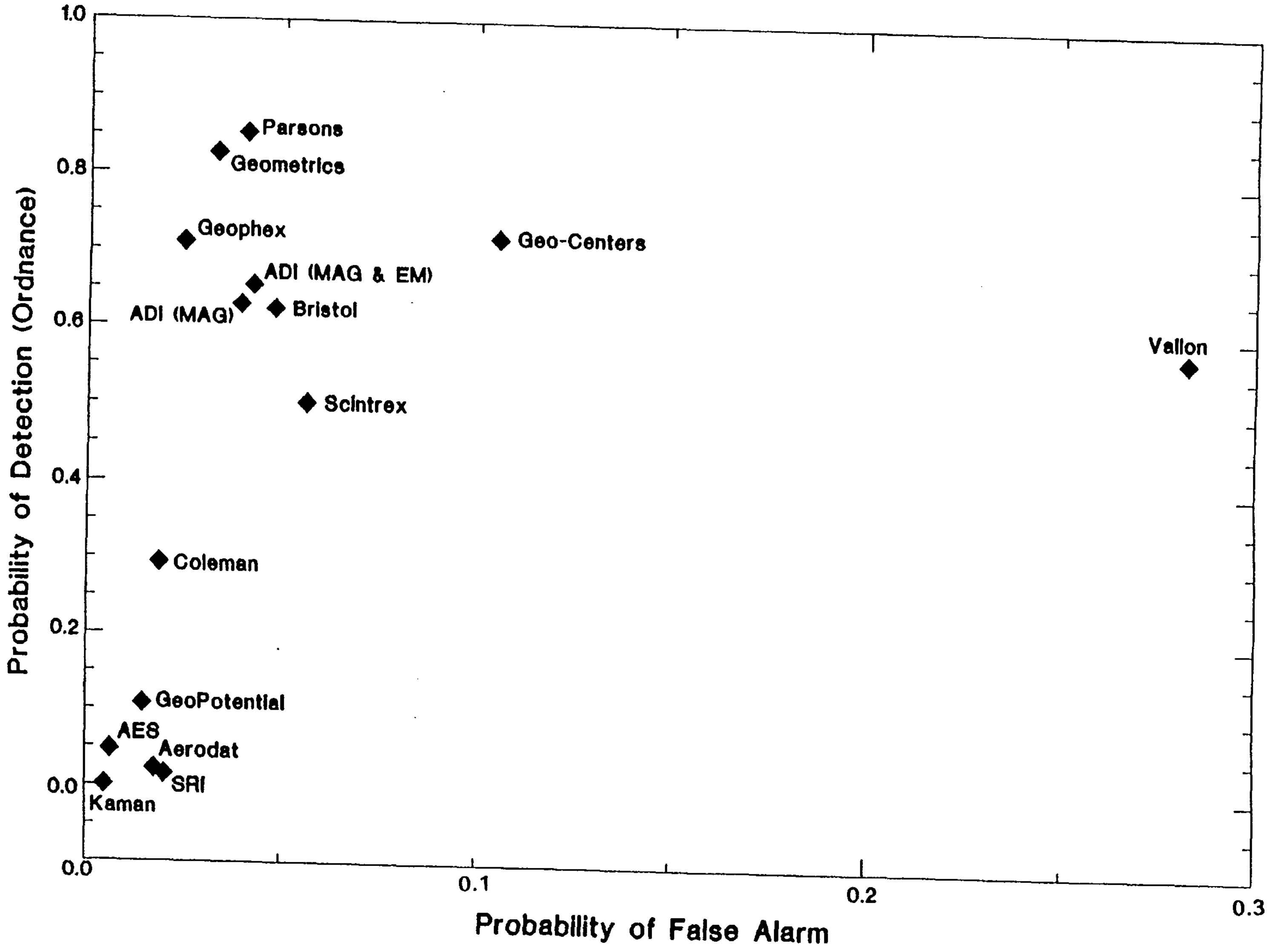


FIGURE 2 DEMONSTRATOR LOCALIZATION PERFORMANCE

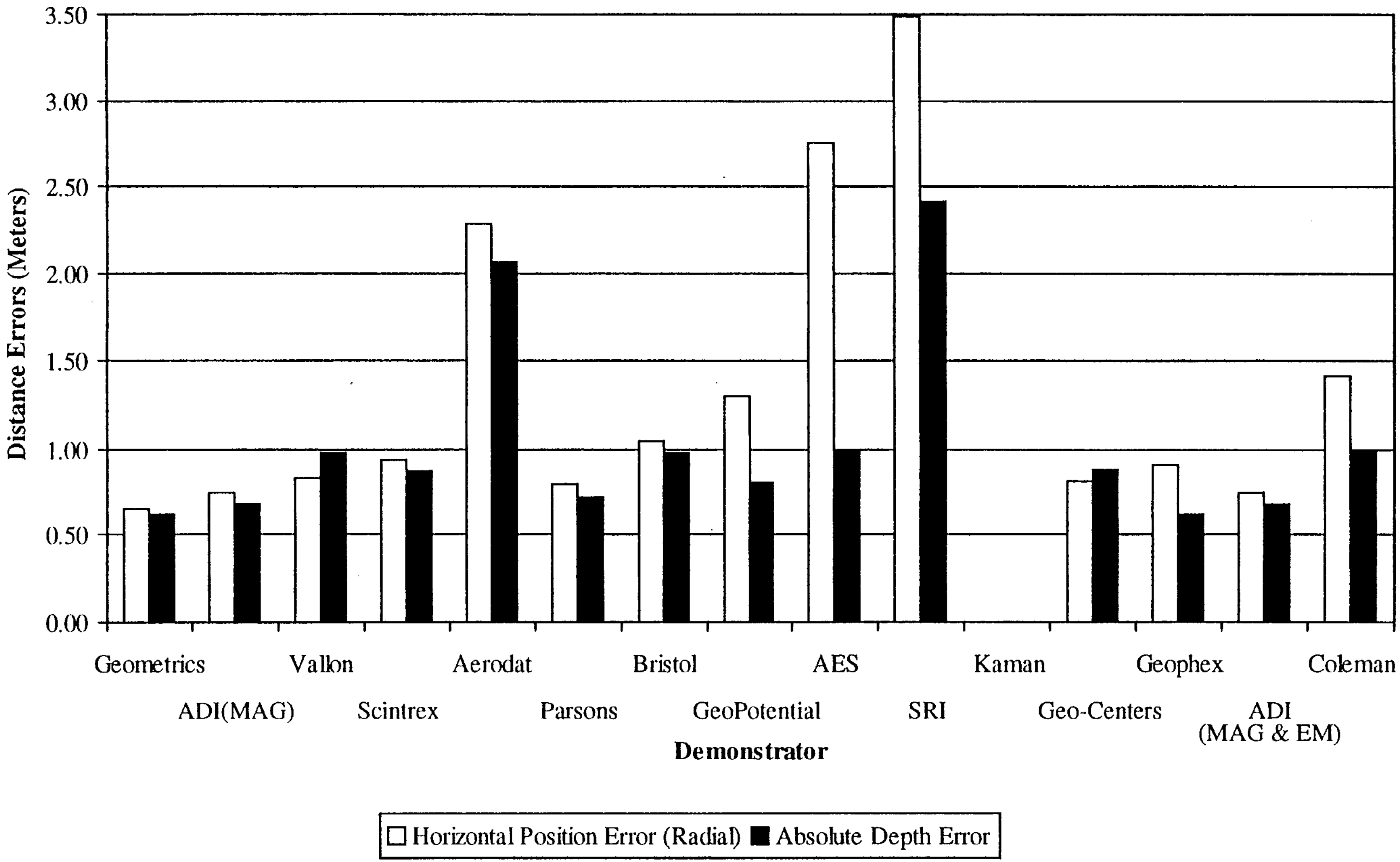
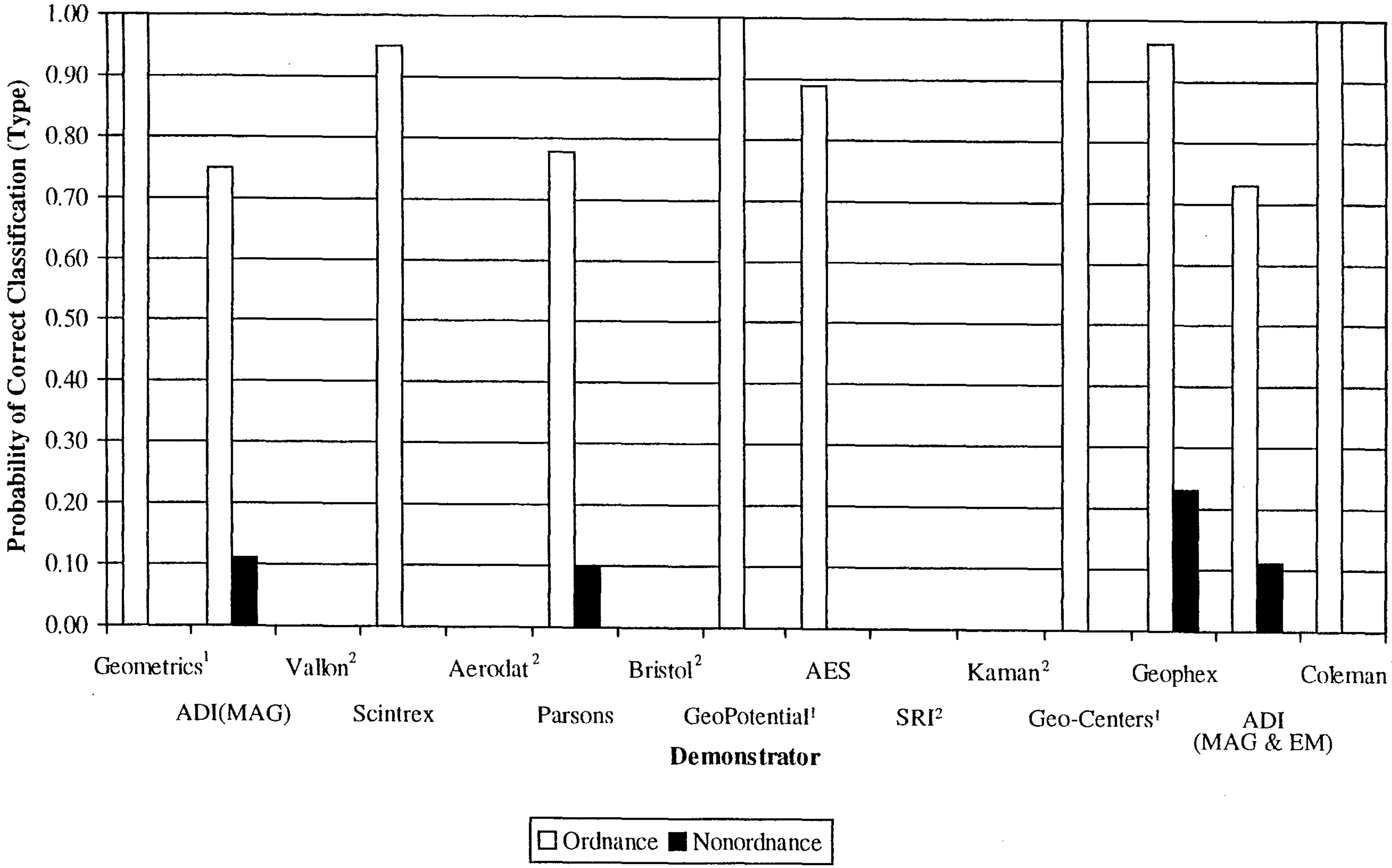


FIGURE 3 **DEMONSTRATOR PROBABILITY OF CORRECT CLASSIFICATION BY TYPE**



Notes: [1] Demonstrator reported all target declarations as "ordnance"

[2] Demonstrator did not provide type information for declarations or listed as "unknown"

EVALUATION OF SUBSURFACE ORDNANCE DETECTION SYSTEMS IN A LIVE ORDNANCE ENVIRONMENT

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ABSTRACT

With the U.S. Army Environmental Center and the Naval Explosive Ordnance Disposal Technology Division, PRC Environmental Management, Inc., is conducting a testing and evaluation program for subsurface unexploded ordnance (UXO) detection, characterization, and remediation advanced technologies. The advanced technology demonstration (ATD) program was initially established within a controlled test range. Some of the technologies that were demonstrated at the controlled test site were selected for participation in ATDs at one or more of five live sites to evaluate technology performance under realistic field conditions. This paper discusses the UXO detection capabilities of tested systems only. Demonstrators were allowed a set time period to conduct UXO surveys at the live sites. Demonstrators were evaluated based on their ability to detect inert ordnance emplaced at the sites by the project team as well as their ability to detect undocumented subsurface UXO. Results of the live site ATDs indicate that the performance of the UXO detection systems generally improved since the controlled site trials in which they were first demonstrated. However, further technology development is needed before UXO detection systems are fully effective.

INTRODUCTION

With the U.S. Army Environmental Center (USAEC) and the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), PRC Environmental Management, Inc. (PRC), is conducting a testing and evaluation program for subsurface unexploded ordnance (UXO) detection, characterization, and remediation advanced technologies. The primary goals of the live site ATD program are to:

- Collect data to assess the capabilities of state-of-the-art UXO detection, identification, and remediation technologies under realistic site conditions

- Identify baseline performance criteria and requirements for site assessment given a technology's capabilities

For the live site ATDs, four major areas of technology performance were assessed, including (1) each system's ability to detect, locate, characterize, and remediate UXO; (2) each system's ability to operate within the constraints of site geology, topography, climate, and other site-specific conditions; (3) each system's logistics requirements for implementation; and (4) each system's performance relative to the other systems tested.

This paper presents the performance of UXO detection systems only; remediation systems are not evaluated herein.

SELECTED RANGES

Based on differences in geology, topography, and climate, five sites were selected for the demonstrations.

- Jefferson Proving Ground (JPG), in south-central Indiana, is a relatively flat site with clay glacial deposits. The two ranges selected for the demonstration are formerly-used artillery impact and practice bombing ranges.

- Yuma Proving Ground (YPG), located in the southwest corner of Arizona, is representative of a sandy desert environment. Two ranges were selected; one has no ordnance history, and the other is primarily used for air-to-ground gunnery and rocketry, although limited artillery, tank, and small-arms training have occurred at the site.

- An air-to-ground gunnery, rocketry, and bombing range was selected at Eglin Air Force Base (AFB), which is located in Florida's panhandle. Soils at this site are sandy and are representative of many coastal regions.

- At Fort Jackson Military Reservation (Fort Jackson), South Carolina, four ranges, all having sandy soils, were selected. These sites were primarily used in the Korean War and Vietnam Conflict as artillery impact and bombing ranges.

- One range at McChord AFB, located near Tacoma, Washington, was selected for the demonstration. The site has gravel and cobble outwash deposits, and has been used by the Air Force since the 1940s for small-arms training. Between 1917 and the 1940s, the Army's Fort Lewis may have used the area.

SELECTED TECHNOLOGIES

NAVEODTECHDIV selected eight UXO detection technologies for the live site ATD project, including Aerodat, Inc.; Australian Defence Industries, Pty. Ltd. (ADI); CHEMRAD Tennessee Corporation (CHEMRAD); Coleman Research Corporation (Coleman); GEO-CENTERS, Inc.; METRATEK, Inc.; SRI International, Inc. (SRI); and Vallon GmbH. Selected technologies were all demonstrated at the 1994 Controlled Site Phase I ATDs at JPG. In addition, demonstrators were selected based on cost and modifications to the technology demonstrated at the Controlled Site. In all, thirteen demonstrations were conducted at the five live sites, with three demonstrators performing surveys at one site each, and the remaining five demonstrators conducting surveys at two sites each.

Selected technologies include magnetometer sensor systems, ground-penetrating radar (GPR) sensor systems, and combinations of GPR and electromagnetic induction (EM) sensor systems. Platforms on which sensors were demonstrated include man-portable, vehicle-towed, fixed-wing aerial, and rotary-wing aerial platforms. Table 1 summarizes each demonstrator's sensor type, platform, and the site(s) at which the demonstrators performed.

FIELD ACTIVITIES

At each of the five live sites, site preparation was one of the most labor-intense activities that took place. For safety reasons, the sites required a pre-demonstration surface sweep and clearance. Active-duty explosive ordnance disposal (EOD) teams, with contractor assistance in some cases, conducted the sweeps. After UXO was identified on the ground surface, it was either destroyed in place or removed for off-site disposal. Many UXO rounds were found during the site sweeps, including artillery rounds, mortar shells, bombs, mines, submunitions, grenades, and small-arms munitions. It is estimated that as a result of the surface sweeps conducted at the live sites, more than 10 tons of UXO-related debris and scrap material were cleared from the surface.

After the site sweeps were complete and proper authorization from federal, state, and local environmental agencies had been obtained, inert UXO rounds were buried at the sites. The targets provide a baseline target set against which demonstrator performance can be evaluated. Typically, UXO similar to that found during the site sweep was placed. Emplaced UXO ranges from 20-mm shells to 2,000-lb bombs, all buried at depths and orientations similar to those that would be found had the UXO actually been fired or dropped upon the site. Emplaced ordnance was surveyed to Third Order horizontal and vertical accuracy.

Demonstrators were allowed up to 120 hours to survey between 40 and 500 acres. All demonstrators were required to survey a 20- to 80-acre area at each site in which the baseline targets were emplaced. After completing their surveys, demonstrators provided NAVEODTECHDIV with a report detailing suspected target locations in three-dimensional space. Demonstrators were also requested to provide information about target type (UXO, non-UXO), target size (small, medium, large), and target class (bomb, mortar, projectile, other). Additionally, demonstrators were requested to assign a confidence to the target declaration.

At each site, a number of demonstrator target declarations were validated, or excavated. The list of targets for excavation is a subset of demonstrator individual and pooled target declaration sets. First, all low-confidence and non-UXO targets were eliminated from the list of potential validation points. Next, small targets were omitted, as the earth-moving equipment typically makes it difficult to identify small targets as they are excavated. Up to 20 validation points were selected randomly from

each demonstrator's reduced target set, and up to 10 validation points were selected from each the set of target declaration "matches" between two demonstrators at the same site.

The validation positions were excavated using military ordnance remediation technology. These technologies include those developed by the U.S. Air Force/Wright Laboratory (Tyndall AFB), YPG Explosive Test Operators (YPG), and U.S. Air Force 96th EOD (Eglin AFB). The excavations were conducted from a remote command booth, typically 1 kilometer or more from the excavation, and suspected contacts were evaluated in the field by the EOD team assigned to the project. After the validation was completed, emplaced targets were excavated and removed, and the sites were restored to their predemonstration conditions.

Safety was an important issue during the live site ATD project, with UXO being the most obvious and primary concern. In addition to the risk from explosion, chemical rounds were suspected at some sites, primarily due to lack of information to the contrary. White phosphorus (WP) rounds at JPG caused the ATD team to approach part of the affected survey area cautiously. As the ground dried in the early summer, fissures in the clay soils allowed air to reach underground WP, occasionally releasing this hazardous chemical. UXO provided only part of the hazards encountered at the sites. Radio frequencies used by the demonstrators in their sensing equipment, and by the communications radios, has the potential to set off UXO with a radio frequency-based fuze. Weather was also of great concern, particularly lightning. Severe storms shut down the project for short periods of time throughout the demonstration period at each site, and Hurricane Erin slowed work at the Eglin AFB site. Finally, biological hazards, including poisonous snakes, scorpions, and insects posed some hazards to the demonstrators. Despite these hazards, no major safety incidents occurred.

EVALUATION CRITERIA

Aerial platform demonstrators were evaluated using a 5-meter critical radius (R_{crit}), and ground platform demonstrators were evaluated using a 2-meter R_{crit}. The R_{crit} value is defined as the radius within which a target declaration is scored as a "hit" on a baseline target. R_{crit} values were developed during the Phase I Controlled Site ATD and correlate well with demonstrator-published radial accuracy values.

By comparing demonstrator reports with the baseline target set, probabilities of detection, or P_D values, can be calculated. P_D values are calculated by dividing the number of baseline targets detected by the total number of baseline targets in the area surveyed by the demonstrator. In addition, because a random placement of declarations could result in "hits," a statistic called P_{random} was developed for the ATD program. P_{random} is a function of the number of targets declared by a demonstrator, the area surveyed by that demonstrator, and the R_{crit} used for the evaluation, and the statistic is used to measure how many of a demonstrator's target declarations might be related to random declarations, sensor noise, or other random effects. P_{random} is compared with demonstrator P_D values to determine whether or not a demonstrator's performance may be the result of these random effects.

RESULTS

Table 2 summarizes P_D, P_{random}, radial, and vertical accuracy values calculated for each demonstrator. As the table shows, discrepancies between aerial and ground platform demonstrators exist. Magnetometer systems outperformed the GPR and EM/GPR combinations in detecting and characterizing subsurface UXO. Sensors mounted on aerial platforms were less likely to detect or properly characterize subsurface UXO than ground platforms.

This analysis does not consider the very important issue of false alarms. False positive target declarations are defined as target declarations at locations that do not contain UXO. False positive declarations result in costly digging at a remediation site, and demonstrators with low false positive declarations are desired to keep remediation costs down. False negative declarations are defined as those locations containing UXO to which demonstrators did not assign a declaration of UXO. False negatives result in UXO being left on site after a remediation is completed; resultant risk to human life continues to exist. Because of the nature of the sites (i.e. they contain unknown quantities of UXO), it is not possible to calculate the false alarm rates described here. These rates can be crudely estimated from the validation data. However, these data are out of the scope of this paper and are not presented herein.

CONCLUSIONS

As a result of the live site demonstrations, it was found that P_D values realized at the live sites improved slightly over the values achieved by the demonstrators at the 1994 Phase 1 Controlled Site ATDs. It is expected that their false alarm rates are also similar.

In addition, demonstrator detection ratios were typically similar from site to site, indicating that geology may not play as significant a role in demonstrator detection ability as thought before the demonstrations began. Also, most demonstrators slightly improved their detection capability from the controlled site to the live sites. These phenomena are shown in Figure 1.

UXO detection technologies have significantly improved over the past few years, and the experience gained by technology developers at the Controlled Site and Live Site ATDs has been instrumental in many of these improvements. Nevertheless, it is clear that further technology development is needed for single-pass searches to effectively and accurately characterize sites containing UXO. The program is currently investigating the prospect of conducting ATDs at several live ranges within all branches of the military, helping to meet the need for technology development while meeting the needs of active military installations as well as formerly-used defense and base realignment and closure sites.

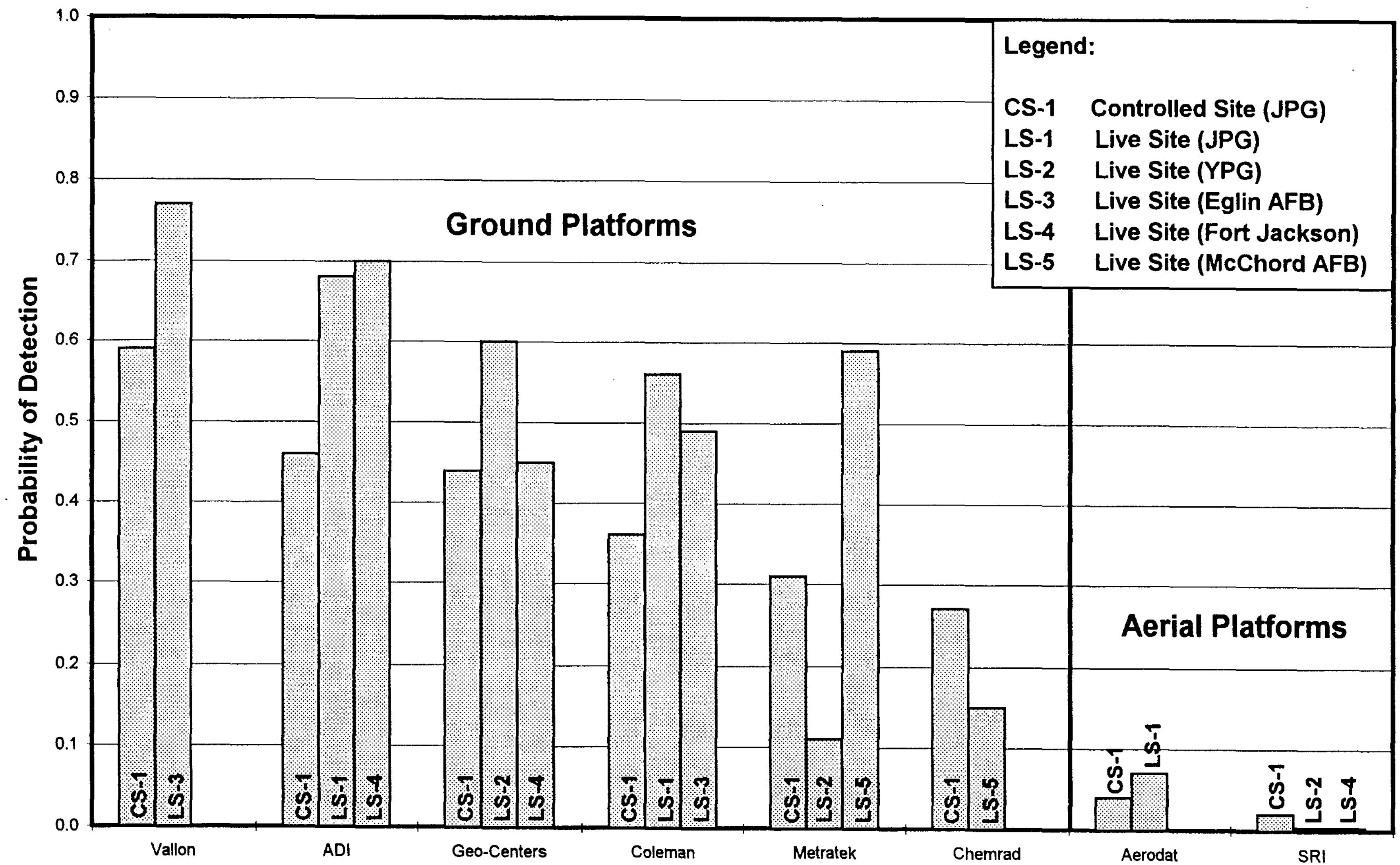
Table 1
Live Site ATD Technology Demonstrators

Demonstrator	Ground Platform		Aerial Platform		Sensor Type			Demonstration Sites				
	Man-Portable	Vehicle-Towed	Fixed-Wing	Rotary-Wing	Magnetometer	GPR	GPR/EM	JPG	YPG	Eglin AFB	Fort Jackson	McChord AFB
Aerodat				✓	✓			✓				
ADI	✓				✓			✓			✓	
CHEMRAD	✓				✓							✓
Coleman		✓					✓	✓		✓		
GEO-CENTERS	✓	✓			✓				✓		✓	
METRATEK		✓					✓		✓			✓
SRI			✓			✓			✓		✓	
Vallon	✓	✓			✓					✓		

Table 2
Demonstrator Measures of Performance

Demonstrator	Platform	Site	P_D	P_{random}	Mean Radial Error (meters)	Mean Absolute Depth Error (meters)
Magnetometer Sensor Systems						
Vallon	Multimodal	Eglin AFB	0.74	0.59	1.09	0.89
ADI	Man-Portable	JPG	0.71	0.08	0.68	0.16
ADI	Man-Portable	Fort Jackson	0.69	0.12	0.73	0.97
GEO-CENTERS	Vehicle-Towed	YPG	0.60	0.21	0.89	0.61
GEO-CENTERS	Multimodal	Fort Jackson	0.45	0.21	0.75	0.33
CHEMRAD	Man-Portable	McChord AFB	0.14	0.14	1.22	0.66
Aerodat	Aerial	JPG	0.07	0.11	4.25	0.61
Ground-Penetrating Radar and Electromagnetic Induction Sensor Systems (Combined)						
METRATEK	Vehicle-Towed	McChord AFB	0.61	0.05	1.13	0.43
Coleman	Multimodal	Eglin AFB	0.55	0.40	1.30	2.27
Coleman	Multimodal	JPG	0.54	0.18	1.14	1.20
METRATEK	Vehicle-Towed	YPG	0.11	0.08	1.18	1.52
Ground-Penetrating Radar Sensor Systems						
SRI	Aerial	YPG	0.00	0.02	NA	NA
SRI	Aerial	Fort Jackson	0.00	0.01	NA	NA

Figure 1
Demonstrator P_D Values by Site



PHASE II CONTROLLED AND LIVE SITE UNEXPLODED ORDNANCE DETECTION, CHARACTERIZATION, AND REMEDIATION ADVANCED TECHNOLOGY DEMONSTRATIONS

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Abstract

Millions of acres of U.S. government property are contaminated with unexploded ordnance (UXO) as a result of weapons system testing and troop training activities conducted over the past century at Department of Defense (DoD) sites. Recent DoD downsizing has resulted in the closing of many military bases, many of which are contaminated with UXO. One unexpected result of DoD's downsizing is the attention focused on the unique problems associated with UXO remediation at these closed military bases. The scope of UXO contamination and associated hazards to DoD personnel and the public have created the need for advanced UXO detection, characterization, and remediation technologies. The U.S. Army Environmental Center (USAEC) is the lead DoD agency for UXO clearance technology demonstrations, evaluation, and technology transfer. USAEC's goals include assessment and advancement of the state of the art in UXO detection, characterization, and remediation technologies and the development and validation of data management and decision-making tools. To accomplish these goals, USAEC directed the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) to serve as the technical lead for the advanced technology demonstration (ATD) program.

In 1994, USAEC and NAVEODTECHDIV created controlled test facilities at the U.S. Army Jefferson Proving Ground in Madison, Indiana, to demonstrate and evaluate commercial UXO clearance systems and technologies. Phase I controlled site demonstrations were conducted during the summer of 1994. These demonstrations were followed by the Phase II controlled site demonstrations at JPG and live site demonstrations at five different live impact and bombing ranges in the summer of 1995.

This paper presents the results of the Phase II controlled and live site demonstrations. The overall performance of the demonstrators is presented along with the operational characteristics and limitations of the various systems and technologies evaluated. Individual demonstrator performance statistics are evaluated by sensor type and sensor transport method.

Background

More than 11 million acres of U.S. government property across the country is contaminated with UXO as a result of weapon system testing and troop training activities conducted over the past century at Department of Defense (DoD) sites. After a worldwide study conducted in 1994, the United Nations declared UXO to be the second leading cause of preventable death in the world, estimating that 20,000 civilians lose their lives each year as a result of encountering some form of UXO.

The recent downsizing of DoD and the closure of military bases throughout the U.S. and overseas have generated about 1,900 formerly used defense (FUD) sites and 130 base realignment and closure (BRAC) sites, many of which are contaminated with UXO. Additionally, many active DoD installations are conducting installation restoration (IR) programs to eliminate or minimize UXO problems. One unexpected result of DoD's downsizing was to focus

attention on unique remediation problems of UXO at FUD and BRAC sites. As hundreds of thousands of acres of military land was being readied for transfer to civilian control, the question of how to best address UXO contamination constantly arose. UXO contamination is unique because of the immediate or imminent danger of explosion and catastrophic loss of life and property.

Many UXO contamination problems are obvious and well documented as in the cases of Kaho'olawe Island in Hawaii and JPG in Indiana, where untold millions of rounds of military munitions have been fired and significant quantities of the ordnance remain buried and unexploded. However, UXO contamination is most dangerous when it is unexpected, as in the 1987 case of two small children being killed by an antitank round discovered in their backyard, which was part of a former U.S. Army firing range in California. In addition, UXO contamination can be costly. For example, the transfer to civilian use of Ft. Sheridan in Illinois has experienced extensive delays because of the discovery of a former small arms/morter firing range once used for training purposes.

The scope of UXO contamination and the associated hazards to DoD personnel and the public have created the need for advanced UXO identification, characterization, and remediation technologies. In response to this need, DoD established the UXO Clearance Technology Program managed by the SAEC. The overall mission of USAEC is to develop, coordinate, and oversee environmental programs and policy for the U.S. Army worldwide. Specifically, USAEC is the lead agency in DoD for UXO clearance. USAEC has established the goals of the UXO Clearance Technology Program to include assessment and advancement of the state of the art in UXO identification, characterization, and remediation technologies and the development and validation of data management and decision making tools. These technologies must be proven to be accurate, reliable, and cost-effective. Moreover, the technologies must be able to operate under a wide variety of environmental conditions.

To accomplish these goals, USAEC has entered into an interservice partnership with NAVEODTECHDIV, which serves as the technical lead for the program. The mission of NAVEODTECHDIV is to provide explosive ordnance disposal technology and logistics management for the Joint Services; to develop essential elements of intelligence, equipment, and procedures in order to address UXO problems both in the U.S. and abroad; and to support the peacetime security needs of DoD and other agencies.

In fiscal year 1993, USAEC's efforts expanded to address a congressional mandate for demonstrating and evaluating the performance of commercial systems and technologies for UXO characterization and remediation. USAEC created a 120-acre controlled test facility at JPG and conducted a series of UXO clearance technology demonstrations to establish a technical performance baseline (Phase I). JPG Phase I was originally expected to require a 3-year effort but was accomplished in a 15-month period, with a final technical report being issued in December 1994. The results presented in the JPG Phase I final report clearly demonstrated that the performance of current UXO clearance technologies would not meet the U.S. Government's needs. Therefore, Congress appropriated additional funding in fiscal years 1994 and 1995 to continue the controlled test facility demonstration project at JPG (Phase II) and to expand it to four other environmentally and geophysically different live sites: Yuma Proving Ground (YPG), Arizona; Eglin Air Force Base (AFB), Florida; Fort Jackson, South Carolina; and McChord Air Force Base, Washington.

Phase II Conrolled Site Demonstrations

In fiscal year 1993, the USAEC and the NAVEODTECHDIV created a controlled site consisting of two technology demonstration areas at the JPG in Madison, Indiana. Phase I of the UXO ATD demonstrations (ATD) was conducted from April through October 1994; Phase II was conducted from May through September 1995.

In preparation for the Phase I technology demonstrations, inert UXO and debris were emplaced at the two controlled demonstration areas. The demonstration areas are referred to as "controlled" because the emplaced items provide a known baseline for the performance measurement of clearance technologies. The controlled site established at JPG was a 48-hectare site (120 acres) consisting of a 16-hectare (40-acre) area for ground system demonstrations and a 32-hectare (80-acre) area for airborne system demonstrations. These areas were selected based on review of historical information and site evaluations, which indicated that the areas were minimally contaminated with UXO and exhibited no significant National Environmental Policy Act (NEPA) concerns. The areas were surveyed, and a 16.5- by 16.5-meter (50- by 50-foot) grid system was established in each area. The areas were then prepared for the demonstrators by emplacing inert ordnance and nonordnance items at depths and orientations typical of UXO-contaminated areas. The position of each item was measured by a licensed surveyor and recorded in a target database to provide a baseline against which demonstrator performance could be measured. The items were then

buried, and their locations were reseeded to match the overall test area. Demonstrators tested their detection and remediation technologies in these areas (USAEC 1995).

The program was conducted in two phases. For Phase I, 31 demonstrations took place from April through October 1994 (PRC Inc. 1994). The systems demonstrated included man-portable, vehicle, combination man-portable and vehicle, airborne, and remediation systems. A variety of different sensor technologies were demonstrated including magnetometer systems, conductivity systems (electromagnetic/induction), ground penetrating radar (GPR) systems, and infrared systems, including combinations of the above.

For both Phases, a standardized data entry program was developed to ensure data uniformity. Measures of effectiveness were developed to provide a technically meaningful framework for assessing demonstrator performance. The measures of effectiveness were based on a target-matching algorithm developed for this project. The measures of effectiveness were expressed as target detection ratios, (percentages of emplaced targets located by each demonstrator); classification ratios (percentages of emplaced targets correctly identified by each demonstrator); error ratios (percentages of each demonstrator's reported targets declared to be incorrectly identified ordnance); and additional data, such as the size, class, depth, and relative orientation of each target. Demonstrator data were collected, entered into the target database, and analyzed using the target-matching algorithm. The results of Phase I were presented in a December 1994 report (PRC Inc, 1994). Ground based system overall detection ratios ranged from 1 to 65 percent. Airborne systems received overall detection ratios between 0 and 8 percent. The remediation systems demonstrated during Phase I operated at a slow rate, but proved successful in excavating targets.

Potential demonstrators that were unable to respond to the Phase I request for proposals or were not accepted for Phase I had the opportunity to submit proposals for Phase II along with new potential demonstrators. Demonstrators who performed under Phase I were eligible for Phase II if significant improvements or changes had been made to their systems. Interested companies submitted proposals for conducting demonstrations at the controlled site. Selection criteria included technical approach, experience, and best value to the government. A total of 17 systems were accepted by the government panel for Phase II, including one government remediation system.

Phase II was conducted from May through November 1995. The 17 systems demonstrated in Phase II included six man-portable systems, two vehicle-towed systems, four combined man-portable and vehicle-towed systems, three airborne systems, and two remediation systems. The 15 detection demonstrators utilized magnetometer systems, electromagnetic induction, and GPR systems, as shown in Table 1.

The objective of the UXO-ATD program is to obtain system capability and performance data on various UXO detection, identification, and remediation technologies. Demonstrators with search systems were required to report the locations and characteristics of emplaced inert ordnance targets. Remediation system demonstrators were required to excavate targets at known locations. The objective for Phase II was to evaluate systems and technology that were not demonstrated during Phase I and those that had made changes to improve performance.

An analysis of demonstrator results from the controlled site UXO-ATDs was performed to assess the performance of the respective systems. The performance analysis was performed in three areas. The first area of analysis was concerned with the detection performance (P_D) of these systems; that is, how well the system detected buried items. The second area was concerned with localization performance, or how accurate the system was in determining the horizontal position and depth of the buried items. The final area of analysis was concerned with the classification performance of the systems. Classification is the ability of a system to determine the type (ordnance or nonordnance), size, and class of the detected item. As part of the classification performance analysis, an analysis was performed to determine how a demonstrator's performance would impact its effectiveness in a remediation scenario.

Fifteen UXO detection systems and two remediation systems were demonstrated from May through September 1995. Detection system technologies included four magnetometer, four electromagnetic induction or electromagnetic induction coupled with GPR, three GPR alone, and five systems that combine either magnetometer and electromagnetic induction technologies or magnetometer and GPR technologies. Of the detection systems, six were man-portable, two were vehicle-towed, four were combined man-portable and vehicle-towed, and three were airborne. Table 1 summarizes the results of detection technologies demonstrated at the controlled site.

Several conclusions are drawn from the data analysis. With respect to the probability that a demonstrator could detect subsurface ordnance (P_D), the best performance was by a

Table 1 Summary of the Phase II Controlled Site Demonstration Results

DEMONSTRATOR	PROBABILITY OF DETECTION	FALSE ALARM RATE
MAGNETOMETRY DEMONSTRATORS		
ADI-MAG	0.63	34.5
AERODAT	0.02	2.3
GEOMETRICS	0.83	26.7
SCINTREX	0.50	45.3
VALLON	0.57	225.9
ELECTROMAGNETIC/CONDUCTIVITY DEMONSTRATORS		
BRISTOL	0.62	38.2
GEOPOTENTIAL	0.11	12.0
PARSONS	0.85	32.5
GROUND PENETRATING RADAR DEMONSTRATORS		
AES	0.05	0.9
SRI	0.02	2.6
KAMAN	0.00	4.2
MULTI-SENSOR DEMONSTRATORS		
ADI-COMB	0.65	31.7
COLEMAN	0.29	15.9
GEOCENTERS	0.72	84.0
GEOPHEX	0.71	19.7

magnetometer system. However, as a group the systems employing multiple sensor types performed better than the other groups (Table 1). The higher P_D values for these demonstrators may be due to two primary factors, including (1) collection of redundant data sets, and (2) collection of additional information by the second sensor type. Combinations of magnetometer and electromagnetic induction technologies also fared better than the other demonstrator groups at characterizing UXO.

Combined man-portable and vehicle-towed systems also performed better than either type of system alone. This performance is probably due to the increased coverage of the site made possible because the vehicle-towed system covers more ground while the man-portable system is more versatile.

Two ground system demonstration areas were used, the 16A-hectare (40A-acre) area that was used during the Phase I controlled site ATD, and the 16B-hectare (40B-acre) area, which is a new area established for the Phase II ATD. A comparison between demonstrator performances at the two areas shows that P_Ds at both areas were quite similar. However, demonstrator false alarm rates (any demonstrator declaration not corresponding to a baseline ordnance target) were much higher at the 16B-hectare area, probably due to the suspected amount of nonordnance clutter present at the site.

Live Site Demonstrations

Based on their performance at the Phase I controlled site ATD, NAVEODTECHDIV selected nine UXO detection system demonstrators to perform at the live sites; however, only eight opted to participate in the program. In addition, four remediation technologies were demonstrated. U. S. Air Force/Wright Laboratories used its autonomously operated excavator (AOE) system at JPG and Ft. Jackson. At YPG, Eglin AFB, and McChord AFB, installation civil engineering or explosive ordnance disposal (EOD) personnel conducted remediation activities using installation-specific excavator systems.

At each of the sites, demonstration activities included a UXO sweep and surface clearance, site survey, controlled target selection and emplacement, demonstrator survey, and validation.

EOD technicians conducted UXO surface sweeps at each of the live sites to clear UXO, ferrous debris, and other miscellaneous rubbish that could adversely affect demonstrators. Items removed from each site were stockpiled near the range on which they were found or removed from the site by the EOD technicians. Overall, more than 4 metric tons of UXO were removed from the sites during the surface sweeps. In addition, some sites required a controlled burn or mowing to reduce the amount of shrubs and vegetation at those sites.

After the UXO sweep and surface clearance activities were completed, NAVEODTECHDIV established at least two site-specific survey control points on or near each of the live site ranges, and at least three survey control points at each live site. The control points are used by the demonstrators to accurately locate UXO. In general, demonstrators required that survey control points be of first order horizontal and second order vertical accuracy. At each range, a 50-meter grid was established. Grid nodes were surveyed to third order accuracy, and wooden stakes were placed at each grid node.

To evaluate demonstrator performance, inert ordnance items, or baseline targets, were emplaced at each of the live sites. The baseline targets selected for each site were generally representative of the types of ordnance used at that site, and range in size from 20-mm projectiles to 2,000-pound bombs. Baseline targets were emplaced at positions and depths similar to what would be expected had they actually been deployed at the site.

Each of the live site demonstrations was scheduled during a continuous 3-week period. Each demonstrator was allowed between 80 and 120 hours during this 3-week period to conduct its survey of between 20 and 120 hectares.

Demonstrator target declarations were validated in the field at the conclusion of each live site demonstration. Data validation involved excavation at demonstrator target declaration locations, and was accomplished using remote excavation equipment at all sites except McChord AFB.

The performance statistics varied widely among demonstrators (Table 2). One demonstrator detected no ordnance at either of the two sites at which it performed its survey. Another detected 74 percent of the emplaced targets. Of the thirteen demonstrator surveys, the average probability of detection was 0.40; the median value was 0.55.

Magnetometer systems performed better than other sensor systems, although a combination of electromagnetic induction (EM) and GPR systems performed nearly as well as the magnetometer alone systems. Magnetometer systems were also better at locating the ordnance, typically exhibiting offset from actual UXO locations within 90 cm.

Table 2 Summary of Live Site Demonstration Results

DEMONSTRATOR	SENSOR	PROBABILITY OF DETECTION
JEFFERSON PROVING GROUND		
AERODAT	MAGNETOMETRY	0.07
ADI	MAGNETOMETRY	0.71
COLEMAN	MULTI-SENSOR	0.54
YUMA PROVING GROUND		
GEO-CENTERS	MAGNETOMETRY	0.60
METRATEK	MULTI-SENSOR	0.11
SRI	GROUND PENETRATING RADAR	0.00
EGLIN AIR FORCE BASE		
COLEMAN	MULTI-SENSOR	0.55
VALLON	MAGNETOMETRY	0.74
FORT JACKSON		
ADI	MAGNETOMETRY	0.69
GEO-CENTERS	MAGNETOMETRY	0.45
SRI	GROUND PENETRATING RADAR	0.00
McCHORD AIR FORCE BASE		
CHEMRAD	MAGNETOMETRY	0.14
METRATEK	MULTI-SENSOR	0.61

Other systems exhibited offsets averaging 120 cm.

The results of the live site ATDs show that ground-based system platforms perform significantly better than aerial platforms. Portable systems performed best, followed by vehicle-towed and then multi-modal platforms. Portable systems were also better at locating UXO, typically locating the baseline targets within 75 cm. Other systems averaged a nearly 120 cm offset.

None of the aerial platform demonstrators performed well at detecting or locating subsurface UXO, although their effectiveness at surveyed areas of surface contamination were not evaluated. Nearly all the demonstrators used differential Ground Penetration System as a navigational system. However, two demonstrators used a manual navigation system or a manual system in conjunction with GPS, and another used an ultrasonic navigation system. The demonstrators using manual navigation as all or part of their navigation system performed better than the other demonstrators. The ultrasonic navigation system did not perform well.

All of the sites selected for the ATD program were found to contain UXO contamination to some degree or another. The McChord AFB site contains the lowest density of UXO, and the UXO found at that site is restricted to small-arms munitions. The Eglin AFB site contains the highest density of UXO encountered during the live site ATD; some locations contain more than 80 UXO items within a 2-meter radius to a depth of 2 meters. Demonstrators at this area classified more of the detected ordnance correctly than those at the 16A-hectare area, probably as a result of system improvements since their participation in the Phase I controlled site ATD.

The support needs of the demonstrators varied greatly, but all of the systems demonstrated at JPG required NAVEODTECHDIV-established facilities and equipment to some extent. Local support services were also required by many of the demonstrators to continue field activities. Remediation systems required a great deal more local support than the detection systems. Consideration of technology-specific support needs is required to implement these systems in remote locations.

The capabilities and limitations of the various detection systems were influenced by the type of system demonstrated, the terrain at the demonstration areas, and the weather conditions. Man-portable systems were more durable and were able to access the entire site successfully, but these systems were limited by the speed and stamina of the field equipment operator. Vehicle-towed systems covered the site quickly but were often subject to breakdowns that caused time-consuming delays. Combined systems took advantage of the strengths of each system while overcoming single system weaknesses. Airborne systems, while yielding the best coverage and speed, lagged behind other systems in detection, localization, and classification ability.

Ground-based detection systems using global positioning systems (GPS) had difficulty maintaining GPS satellite lock in forested areas, while those demonstrators using manual navigation systems experienced little trouble with navigation systems.

Phase II Controlled Site Results

The Phase II demonstrator results indicated magnetometry systems faired best and that the multi-modal systems (two different types of sensors used to investigate the area) did better than the single systems. The ability to correctly identify the size of an object varied appreciably between sensor technologies and demonstrators.

Only three demonstrators reported ordnance and nonordnance targets. The reported nonordnance targets were significantly lower than the ordnance targets. This may be due to 'err on the side of safety' philosophy with respect to ordnance detection. Demonstrators were also asked to classify ordnance targets. Most demonstrators were able to classify bombs and with some success, projectiles and morters. None of the demonstrators successfully identified ordnance clusters.

Man-portable systems were the most durable (not considering operator endurance) and they had no difficulty accessing all portions of the site. Vehicle towed systems covered open areas two to three times faster than man-portable systems, but appeared to subject to breakdown and had difficulty accessing certain portions of the site. The combined systems appeared to have an advantage, utilizing the speed of the towed platform in open, relatively flat areas and incorporating the accessability of the man-portable units in the forested and heavily vegetated areas and rough terrain. The airborne systems had the best coverage and speed, but detection numbers from these systems are still very poor (less than 0.1) with no classification ability.

The overall Phase II results indicate that multi-modal systems performed better than either man-portable or vehicle-towed sensor systems. Combinations of magnetometer and electromagnetic induction systems performed the best of the multi-sensor systems.

Comparison of the Phase I and the Phase II data indicates that there was a slight improvement in demonstrator results during the Phase II effort. This may be due to the increased use of multi-modal systems during Phase II. These systems not only provide better coverage, but they also provided double coverage of some areas with two different sensors.

Robotic remediation systems performed at a rate of five to fifteen holes per day at the Controlled Site.

Live Site Results

As a group, ground platform demonstrators detected and properly characterized targets better than aerial platforms. Of the ground platforms, portable systems had higher detection rates and exhibited better location capabilities than vehicle-towed or multi-modal systems. The magnetometer systems outperformed the GPR and the EM/GPR combinations in detecting and correctly characterizing baseline targets.

As a result of the live site validation process, ground platform demonstrators outperformed the aerial platform demonstrators, with portable and multi-modal platform demonstrators detecting more of the excavated targets. The magnetometer sensors outperformed the other sensor types. The detection rate for ordnance and nonordnance targets was comparable to the detection rate for demonstrator performance against the baseline targets.

Robotic remediation systems performed at an average rate of two to six holes per day. Surface and near-surface ordnance accounted for most of the material at the live sites.

Program Results to Date

Demonstration technologies have improved from Phase I to Phase II. Some of the reasons for this improvement include the improved performance of repeat demonstrators, the increase in use of multi-modal and multi-sensor techniques, and the increase in teaming arrangements among technology providers.

The detection values of the best systems increased from a high of 0.60 during Phase I to a high of 0.85 during Phase II. Unfortunately, most of the best performing demonstrators swept about1 acre per hour. The live site demonstrations indicate that detection values are not significantly different between sites with different geologic characteristics. In addition, the live site validation testing confirmed false alarm predeictions from the controlled site testing.

The accomplishments to date at JPG include, conducting 50 demonstrations, evaluating 40 different systems, and comparing and contrasting data sets within three baseline target sets, obtaining unique field data on detection, localization and classification. At the live site the detection values were comparable regardless of geologic or environmental conditions. The validation of unknown target declarations at the live site showed that the detection values and false alarm rates were comparable to performance against known baselines.

Program Needs

A review of the UXO ATD progam to date has resulted in the identification of the following program needs:

- Improve detection capabilities
- Improve the ability to chacterize ordnance to lower the false alarm rate
- Develop and evaluate new detection technologies
- Improve survey and remediation speed
- Develop and evaluate more remediation techniques for surface and subsurface munitions

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A SYSTEM FOR PERFORMING SITE REMEDIATION FOR TEST RANGES CONTAINING UNEXPLODED ORDNANCE

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ABSTRACT

The Government effort to rightsize the Department of Defense (DOD) forces and facilities has some far reaching implications including the turnover of DOD ordnance test ranges to the public. It will be DOD's responsibility to ensure that those ranges are free from the hazards of unexploded ordnance (UXO). The Naval Explosive Ordnance Technology Division (NAVEODTECHDIV) is the DOD designated research facility for Explosive Ordnance Disposal (EOD) and has accepted the mission to assess and develop the technologies to accomplish the Area Clearance/Range Remediation task. The Area Clearance mission is composed of two separate subtasks, characterization of the area of interest, and remediation of that area based on the findings of the characterization.

Because of the hazardous nature of the task, one of the program goals is to remove the human operator from the immediate area. This is accomplished through the use of robotic platforms. Wright Laboratory (WL) at Tyndall Air Force Base is the Office of Secretary of Defense (OSD) designated lead for construction automation. WL has been tasked by NAVEODTECHDIV to develop the robotic platforms that will perform the remediation tasks. One such system under development is the Automated Ordnance Excavator (Figure 1).

The goal of the remediation task is to render safe the ordnance targets determined in the task of site characterization. There will be three options during remediation which depend on the

Figure 1
Automated Ordnance Excavator and Mobile Command Station

condition of the ordnance and the type of fusing: (1) a shape charge will be placed on the ordnance. (2) the material surrounding the ordnance will be removed to allow free access for the EOD technician (3) the ordnance will be removed from its resting place and placed on a pallet for later disposal. The remediation task can be accomplished by the Automated Ordnance Excavator (AOE) while minimizing risks to EOD personnel. It starts with a map containing target ordnance locations and proceeds to each target, in turn. It will remove the bulk of the material around the ordnance with a conventional bucket and then expose the ordnance for remediation. Once the ordnance has been identified, a method of disposal can be determined to safe and remove the UXO. The AOE uses the same advanced differential Global Positioning System (GPS) for navigation developed on the WL-developed Autonomous Tow Vehicle (a component of the Subsurface Ordnance Characterization System) to accomplish its site characterization task.

BASIC SYSTEM

The Automated Ordnance Excavator is a Caterpillar 325L "Long-Reach" excavator with an extended reach option. The "long-reach" option offers the longest configuration of the tracks which offer the most stable base for digging. The longest extended reach option makes the "bucket-to-machine" distance the maximum possible to offer some protection of the base machine in the event of detonation during remediation of a UXO. The length of reach of this excavator is 60.5 feet horizontally and 48.5 feet vertically. The AOE weighs approximately 65,000 lbs and is considered to be a large-scale remediation platform.

The AOE is powered by a Caterpillar turbocharged and aftercooled 3116 diesel engine with high-pressure, unit injection fuel system. Automatic engine control conserves fuel when manipulation and travel controls are not activated. A monitor panel located in the vehicles cab, provides status information for the operator through a high definition liquid crystal display (Figure 2). The travel and manipulation circuits are powered through two variable-displacement pumps.

OFF-THE-SHELF MODIFICATIONS

Prior to the delivery date for shipment of the excavator to WL, the AOE was sent off for additional factory modifications. This included the addition of a remote control system and manipulator thumb installation. Both available as off-the-shelf options.

Remote Control System

A Vectran remote-control system provides for full remote operation of the vehicle via two radio transmitters (one for data transfer and one for video transfer. Provisions are available for tethered cable control without the video feedback. The data transmitter/receiver uses a propriety Vectran radio operating at a frequency of 163.75 Mhz and less than 2 Watts power. The video transmitter/receiver uses a UHF associates FMCD radio operating at a frequency of 918.5 Mhz and less than 10 Watts power. RF control can be operated remotely up to 2 miles line-of-sight and tether operation up to approximately 2000 feet.

Remote operations include: left and right track operation for propulsion; boom, stick, bucket, swing, and thumb manipulation for digging; and iris, focus, zoom, pan, tilt and

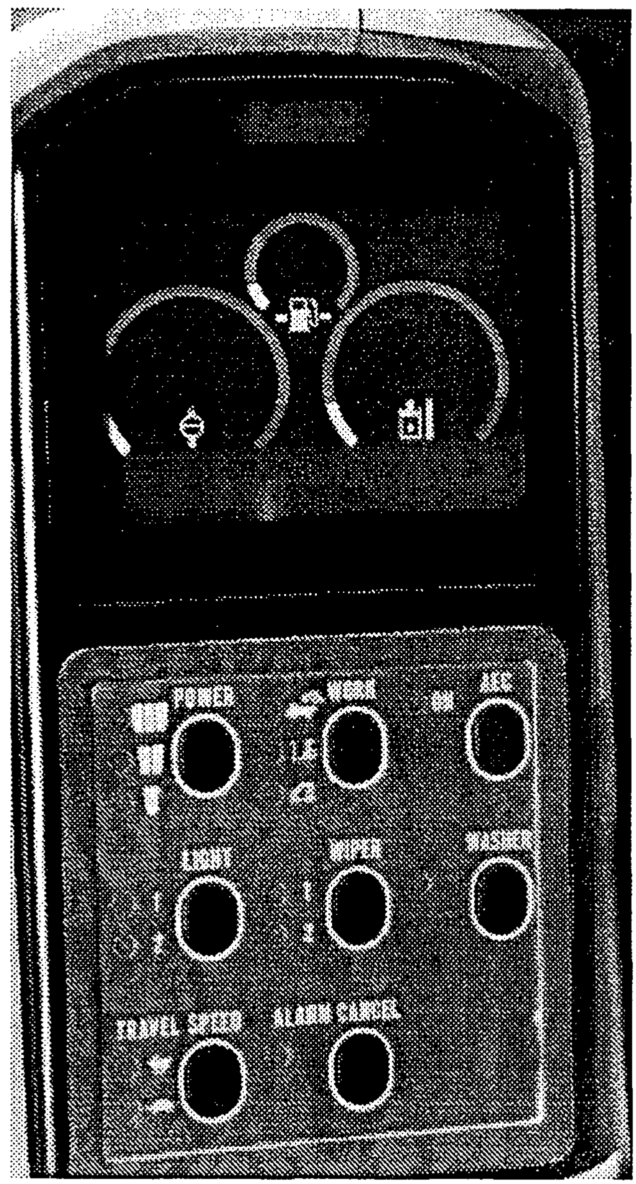

Figure 2
Operator's Liquid Crystal Display

camera selection for video feedback. The camera system implemented by Vectran provided for three remote views; however, only one view can be displayed at any given time. The cameras were located one above the vehicle cab for the driver's point-of-view perspective, one inside the cab to monitor the LCD display panel, and one mounted on the right side of the excavator looking forward for a right-side point-of-view perspective. Both exterior cameras were mounted on a pan/tilt mechanism with approximately 340 degree rotation in the horizontal plane and 90 degree rotation in the vertical plane.

Manipulator Thumb

A Balderson thumb has been installed that gives the AOE an ability to grasp objects. To grasp an object, the thumb is fully extended and the bucket is manipulated until contact with the object. The bucket is then closed and the thumb is back-driven allowing the bucket to fully rotate to bear the load of the object. The object can than be relocated for release.

WL MODIFICATIONS

After receipt of the AOE, WL further modified the vehicle with navigational aids such as GPS, map interface plus other minor improvements.

Navigation System

The primary navigation component for the AOE utilizes an Ashtech differential GPS. This GPS gives the AOE the ability to position itself within centimeters of a desired latitude/longitude. The GPS provides position updates at a rate of 1 hertz. Orientation of the AOE is determined by utilizing the previous latitude/longitude position with the current latitude/longitude. This method provides sufficient orientation information while the excavator is moving; however, inadvertent graphical rotations do occur while the excavator is motionless.

Bucket Teeth

The excavator bucket teeth have been extended by one foot and rounded to match the curvature of a 55 gallon drum or a 2000 lb munition simulating the largest UXO that may be found (Figure3). The bucket's four extended teeth are approximately one foot apart and gives the excavator the ability to rake through the soil to act a sifting mechanism to explore each lift of the soil.

Stick Camera

With the extended reach boom/stick, there was sufficient room to relocate the Vectran right side camera and mount it on the stick approximately 10 feet from the bucket to provide the operator an overhead view. The pan/tilt portion of the camera mechanism was removed; however, it still has zoom, focus, and iris control to allow the operator to zoom in and identify a suspected target.

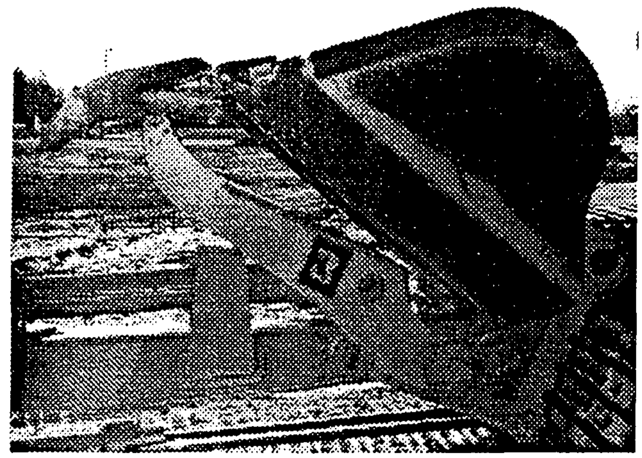

Figure 3
Bucket Teeth

MOBILE COMMAND STATION

Remote operation of the AOE is conducted from a mobile command station. The Mobile Command Station (MCS) provides the operator a controlled atmosphere while operating at a safe distance from the hazards of uncovering a UXO. The MCS provides 110 AC power through a 5KW generator mounted over the passengers cab that is conditioned through a Universal Power Supply (UPS). The UPS unit provides for continuous conditioned power for the operator control unit, navigation computer, GPS units, and other auxiliary equipment and allows the operator time to shutdown these devices in the event of a generator failure.

Navigation Computer

The graphical interface to the operator for map and excavator configuration display is accomplished on a Sun SPARC 2 computer system. The navigation computer receives information about the latitude/longitude and boom/stick displacement. The base station GPS (located in MCS) latitude/longitude is transmitted to the rover GPS (located on the AOE) and is processed by the rover GPS unit to determine its corrected position. The base station GPS antenna is positioned over a known location, preferably a first order monument or a marker on which characterization data was based. This corrected position from the GPS is then relayed to an on-board microprocessor to be formatted with the boom/stick displacement information from displacement string

pots located on each actuator. This information is then relayed to the MCS for display to the remote operator.

Camera System

A 30-foot telescoping mast/turret camera system provides the operator a "bird-eye" view of the remote operation from the MCS (Figure 4). The camera is mounted on a pan/tilt unit capable of 340° degrees horizontal rotation and 90° vertical rotation. The camera has zoom, focus and iris control and is manipulated from within the MCS at the remote operator console.

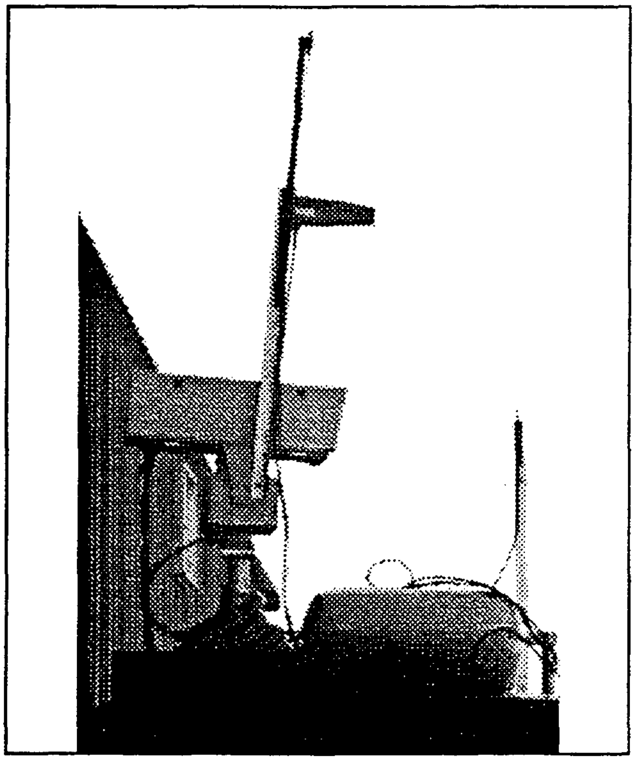

Figure 4
MCS Camera System

Radios

Communications to the AOE is accomplished through the use of several radio transmitters/receivers depending upon the type of information being transferred.

An AACOM transmitter/receiver establishes communication between the AOE and MCS for video transfer. The radio frequency used with the Vectran system often conflicted with local frequencies used in the demonstration areas and frequency authorization could not be obtained. AACOM radios, already authorized at Tyndall AFB, was transitioned to the AOE. The AACOM is a JF12-rated radio operating at a frequency of 1795.5 Mhz. A directional antenna mounted on the mast/turret pan/tilt mechanism is easily pointed at the AOE utilizing the video image feedback from the camera. There is only a manual tracking capability with this camera system.

A Freewave transmitter/receiver, utilizing a spread spectrum method, operates with a tuning range of 902-928 Mhz and provides for the transfer of the GPS navigation and boom/stick information.

Remote Control Interface

The Vectran operator control unit (OCU) is a stand-alone remote interface to the AOE (Figure 5). The OCU houses the joysticks, switches, and radio to remotely operate the AOE. Four joysticks located along the lower bottom of the OCU controls the primary movement of the excavator. The joystick layout mimics the vehicle controls in the cab and there is no difference (latency) from remote operation as manual operation. Both remote and manual operation of the vehicle is accomplished through a parallel arrangement of a pilot hydraulic system.

FIELD TESTING

As the designated OSD lead in construction automation, WL regularly participates in demonstrations to identify and improve each platform and subsystem under development. Some of these demonstration sites include Jefferson Proving Ground (JPG) Controlled Site, Jefferson Proving Ground Live-Site, and Fort Jackson Live-Site.

Jefferson Proving Ground

At the request Congress, the DOD established the JPG UXO Advanced Technology Demonstration Program. The objective of this program was to identify, demonstrate and evaluate the performance of current available technologies used to detect, characterize and remediate subsurface UXO. WL has developed several platforms/technologies that support these UXO and Area Clearance programs. This work is being accomplished under the sponsorship of the Army Environmental Center at the direction of the NAVEODTECHDIV.

In support of the Sep 1994 JPG demonstration, WL demonstrated the AOE as a large-scale remediation system. It is envisioned that the task of remediation will require a range of equipment to cover surface, shallow, medium, and deep buried UXO.

Prior to the demonstration, a local terrain map depicting trees, valleys and other obstacle was fed into the navigation

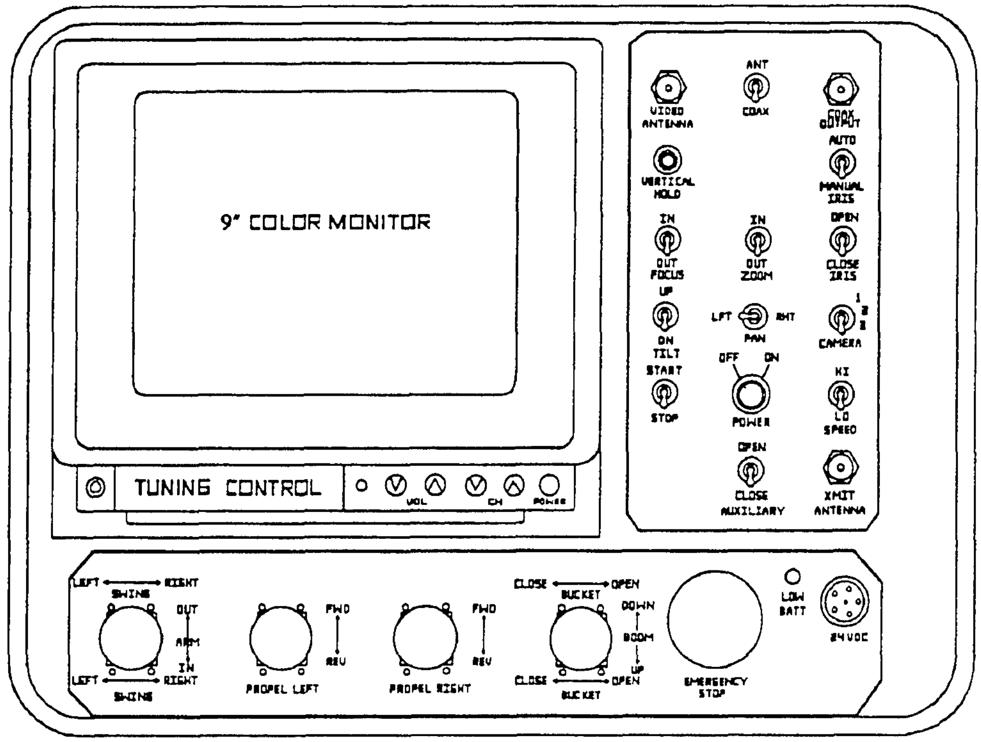

Figure 5
Vectran Operator Control Unit

map. Upon arrival at the JPG controlled site, a target list was given in local measurements of northing and easting and converted to a latitude/longitude for input to the navigation map. Target information contained the location of implanted inert ordnance ranging from small, shallow buried 60mm mortars to a large, deep buried 500lb bombs and also unknown anomalies discovered during the detection demonstrations.

Based upon terrain conditions (i.e., trees, gullies, fences) a target was selected that offered the best approach (preferably line-of-sight between the MCS and AOE) while maintaining a safe stand-off distance to simulate an actual unexploded ordnance remediation. End results showed the AOE was capable of remotely positioning over the target within centimeters. Results also showed the AOE was not well suited for remediating small UXO without the aid of detection system within the bucket. Visual recognition of UXO falling out of the bucket was difficult and targets were often missed. Another difficulty encountered was the ability to reposition the bucket over the target once the soil was disturbed. To solve this problem, the addition of string pots on the boom/stick actuator enabled the AOE to return to the initial position.

Methods for uncovering ordnance and determining if the UXO would be uncovered, removed or detonated in place are not yet established for remote control operations. As remote technology and fine manipulation progresses, methodologies will be established and rewritten.

Live-Site Program

At the conclusion of the Sep 94 JPG controlled site demonstration, a Live-Site program was established that selected the best detection systems demonstrated and tried them on several, contaminated UXO sites. These sites included Jefferson Proving Ground, IN; Yuma Proving Ground, AZ; Eglin Air Force Base, FL; Fort Jackson, SC; and McChord Air Force Base, WA. The AOE participated in two of these sites, JPG and Fort Jackson, to validate the locations that the demonstrators deemed the most probable location at which to find a UXO.

Prior to any remediation or survey, the records of each site were reviewed to determine the expected type of ordnance to be found. Often times records of these sites were vague and inaccurate because prior to the 1980's, record keeping was not mandatory for most installations.

Initially areas are manually swept to clear the surface of any visible ordnance before demonstrators are allowed on the range. Inert UXO were also emplaced to provide the detection systems a means of truthing their data and remediation systems to proof their navigation ability against known and expected UXO types. These UXO was also used to validate the ability of the AOE's navigation system to precisely locate over the target.

Once a site was prepared, demonstrator's were allowed three weeks to cover the maximum area possible. After the surveying phase, demonstrators were given three weeks to identify and rank order their target list. The final phase of the live-site effort was the validation phase. This phase was given three weeks to validate as many targets as possible with a minimum of ten targets per demonstrator.

Validation consisted of excavating a hole a minimum of 9 feet wide by 9 feet long above the designated latitude/longitude down to the depth that the demonstrator estimate it to be. If no UXO was found, excavation continued an additional 3 feet below target depth. After each excavation, the dig site and spoil pile was scanned with metal detection devices to determine the presence of any metal signature.

In the event that objects other than UXO were located, the hole was still excavated to the required maximum dimensions. If an ordnance was found, the demonstrator was awarded a positive hit. If any other object was found that possessed a metallic signature, the demonstrator was awarded a false positive hit. When a non-metallic object or nothing was found, the demonstrator received a false negative. For targets that had multiple demonstrator hits, each demonstrator received the same scoring as a single hit targets.

Jefferson Proving Ground IN, Live-Site

Two sites located on JPG was selected for the demonstrators to survey. Both sites were approximately 1000 feet x 1000 feet. Each demonstrator identified hundreds of possible targets. Due to the saturation of contamination near the surface, any hits within 18 inches from the surface were not considered for validation. This still left hundreds of targets to select from. Further below the surface selection was accomplished by looking at multiple hits at one location from two or more demonstrators. From the remaining list, the top ten individual targets identified by each demonstrator was selected for validation. Targets that had multiple demonstrator hits were investigated separately after the initial 30 targets.

JPG validation efforts revealed several UXO. If a UXO was discovered, EOD technicians identified the type of UXO and directed the method to render the munition safe. Most of the ordnance found at JPG were practice rounds that possess an explosive spotting charge. All the UXO discovered was relocated to the furthest excavated hole for detonation at the end of each day. This prevented further saturation of the area with metal fragments. None of the UXO found possessed a high explosive capability.

Fort Jackson SC Live-Site

Two areas were also selected at Fort Jackson for this effort. The first area was a training area where the US Army practices air drop and battlefield maneuvers. The fields were plowed annually and planted with winter wheat. Records indicated that this area was once used as an impact area but had been cleared of all hazards. The second area selected was still an active impact range and possessed the possibility of producing live, hazardous UXOs. At both sites, the validation method followed the same approach as JPG. Several targets excavated in the maneuver area revealed various building materials, barbed wire, and telephone high tension wires. The only ordnance found and remediated at Fort Jackson was a high explosive 155mm round.

ISSUES

With each demonstration WL evaluates the effectiveness and limitations of the remediation system. We constantly explore new methods for remediating UXOs by remote means and establish operational guidelines for each system. After each demonstration, the team conducts a review of the methods and procedures for optimization or focusing of future technological improvements. For example, a minor problem encountered during the first demonstration was receiving the target list in northing/easting coordinates versus latitude/longitude coordinates. This lead to the establishment of how the target list would be conveyed between a detection system and a remediation system. The remediation system was also enhanced to be able to handle a variety of inputs or have the ability to convert coordinate systems to an acceptable input to the navigation map.

Other problems were discovered such as UXOs being missed during removal of the soil. Smaller UXO were often found in the spoil pile or pushed under the front of the excavator. Sensor technology research is being conducted to help expose or locate the UXO before physically touching the UXO. This research ranges from inductance coil technology to ground penetrating radar technology. Other developments include tools to expose the ordnance with little physical contact such as rotating brushes and air-jet vacuum systems.

FUTURE MODIFICATIONS

As with any mechanical system, reliability and

maintainability are serious concerns. Establishing reliable long distance, line-of-sight RF communications between the AOE and MCS has been a significant factor in determining the requirements for the next generation/modification upgrade for the control of the AOE. The ability to diagnose malfunctions and isolate failed components are of concern as well.

The next generation of the AOE will incorporate a modular approach in the design of the control system. WL is exploring the application of the Controller Area Network (CAN) bus architecture for the control and monitoring of the vehicle. The CAN approach is a network of nodes distributed around the vehicle providing device power and network lines. The design of the network will follow a DeviceNet® specification. DeviceNet manufacturers provide off-the-shelf components (encoders, resolvers, etc.) and direct connectivity to the CAN bus by using CAN power and information feedback through the network. Other devices not DeviceNet compatible can be interfaced through Input/Output modules.

The CAN bus host uses the Lynx® real-time operating system on a ruggedized Radisys 486-50 Mhz PC computer. be easily diagnosed. It is the goal of this phase of development to design components for modularity and the ability to quickly remove and replace a failed part. The DeviceNet specification was selected due to the availability of products made compatible and designed for this specification.

OTHER ROBOTIC PLATFORMS

The AOE is designated as a "low-cost" platform and available off-the-shelf as a teleoperated excavator. The enhancements WL has made to the excavator will be distributed to industry through a technology transfer package. All developments at WL are unclassified and available as public information.

Remote Vehicle Excavation System

WL is sponsored by OSD to extend the state-of-the-art in construction automation. To evaluate and develop potential technologies geared toward vehicle automation and UXO remediation, WL has developed a state-of-the-art testbed excavator called the Remote Vehicle Excavation System (Figure 6).

Figure 6
Remote Excavation Vehicle System

Drivers and diagnostic routines are being develop at WL for the implementation of real-time control of mobile vehicles. The CAN bus, coupled with the diagnostic routine, will provide a reliable, robust platform for field testing. In the event of a failure, the node at which the failure occurred can

This system was designed as a state-of-the-art robotic testbed. Actuators and other devices are designed to be able to provide the most accurate monitoring and precise positioning capability. Future technologies such as different manipulators and tools will have sufficient hydraulic power and positioning

ability necessary. Vehicle navigation is accomplished through on-board computers housed in an environmentally controlled enclosure at the rear of the vehicle and an RF interface with a mobile command station. The Remote Excavation Vehicle System (REVS) is focusing on autonomous/semi-autonomous technologies. Once a system or tool has been proven on the REVS, it is then transitioned to other platforms.

PRECISION EXCAVATION

Two precision excavation technologies currently under development on the REVS are an articulating clamshell and an air-jet vacuum system.

Articulating Clamshell

The articulating clamshell replaces the standard REVS bucket and incorporates a non-sparking rotating brush (Figure 7) to gently uncover a UXO. The clamshell allows excavation of a hole to be controlled very precisely. As detection systems improve, the ability to precisely determine the type, depth, size and orientation of a UXO, the clamshell will offer the remote operator the ability to unearth and grasp the object with minimal impact. This system is expected to be delivered and installed for JPG III demonstrations.

Air-Jet Vacuum System

Similar in concept with the rotating brush gently uncovering the UXO, an air-jet vacuum system mounted at the end of the excavator stick will remove the soil surrounding the UXO without physically jarring it using a high velocity air nozzle/vacuum system. A compressor/vacuum device will be towed by the host vehicle to supply the necessary power.

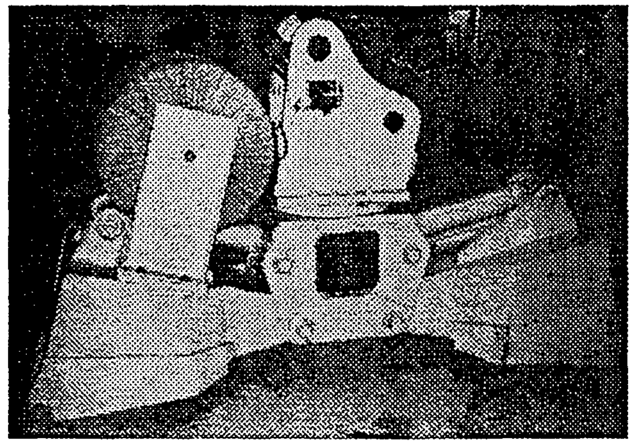

Figure 7
Articulating Clamshell

This system is expected to be delivered and demonstrated at the beginning of FY 97.

CHARACTERIZATION SYSTEM

Subsurface Ordnance Characterization System

WL provides the NAVEODTECHDIV support for the development of an autonomous detection system known as the Subsurface Ordnance Characterization System (SOCS). Leveraging technology from the REVS program, SOCS (Figure 8) is capable of autonomously surveying a plot of land

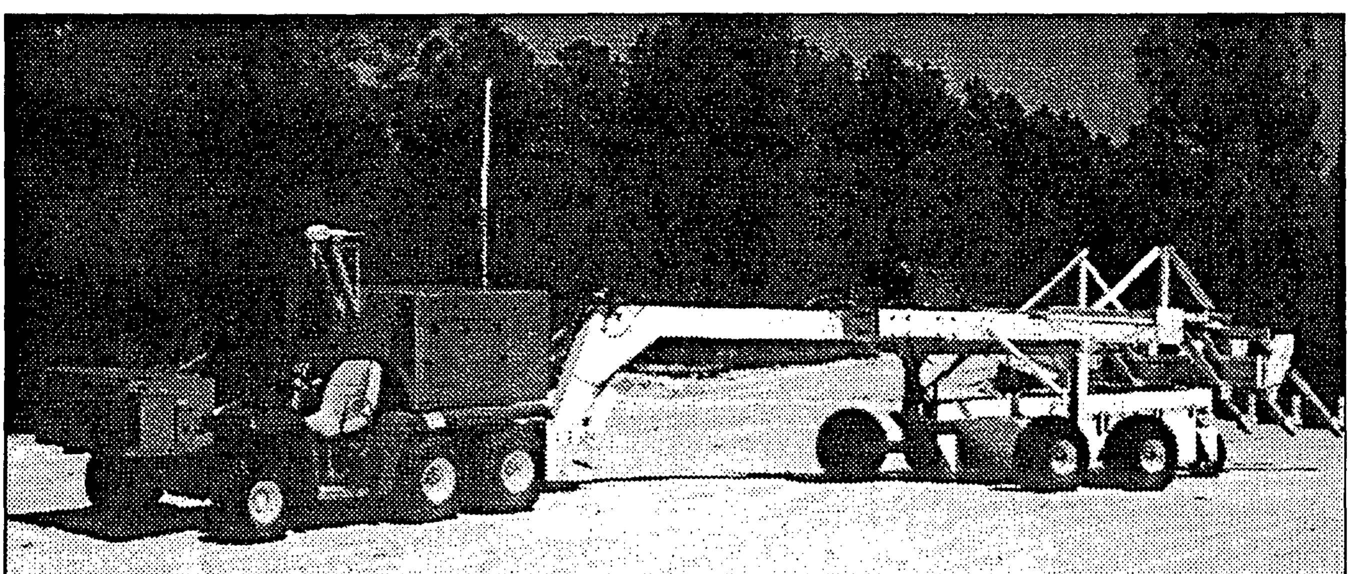

Figure 8
Subsurface Ordnance Characterization System

while accurately characterizing subsurface UXO utilizing a ground penetrating radar and four Cesium vapor magnetometers. SOCS was designed as a test platform for exploring a new sensor technologies.

Leveraging technologies developed under the OSD construction automation program, SOCS uses an identical navigation system as the REVS developed for WL at the University of Florida. A data collection system gathers multiple sensor input and tags the information with navigation time and position data. Later analysis is perform for determining the location, type, depth and orientation of a potential target.

A CASE STUDY OF AN INNOVATIVE ASSESSMENT STRATEGY TRACADIE RANGE NEW BRUNSWICK CANADA

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ABSTRACT

The 18,000 hectare (44,500 acre) Tracadie Range in north-eastern New Brunswick had been used as an artillery, mortar and air to ground training range from 1940 to its closure for those purposes in 1990. In 1994 the Canadian Department of National Defence (DND) determined that it had no future use for the property. As such, it was required to dispose of the property at market value. The disposal process gave the Provincial government a priority interest in acquiring the property, which it exercised. The Province hopes to be able to reopen most of the range to public use. However, like other ranges of the vintage the full extent and level of UXO contamination was not known. Before any transfer could occur those areas affected must be cleared of the hazard of unexploded ordnance to the degree required to allow for the next anticipated land use. To this end, DND has initiated a project to undertake a UXO survey and to prepare a clearance plan for the Tracadie Range. The UXO project was issued to Dillon and its prime sub-contractor, Australian Defence Industries (ADI) in April 1995. The contract, to be executed over two years, will produce a detailed approach and cost estimate to clear identified areas of the range of UXO. The approach to range clearing will be tied to the variety of land uses which are likely to occur on the property after release by DND. The first stages of the project were completed and reported on in December 1995.

In awarding the contract to Dillon and ADI, DND accepted an innovative electronic survey strategy which offered a high degree of confidence that all areas within the range will be correctly categorized. It also claimed better site assessment quality, lower costs, better use of available funds and minimal effect on the environment. The approach used employed a calibrated, statistical sampling procedure that was developed for measuring the density, extent, type and distribution of ferrous UXO contamination. The procedure was designed for efficient, large area operations where heavy forest and rugged terrain may be encountered.

BACKGROUND

As part of its Defence Establishment Reduction 1994 (DER '94) program, the Department of National Defence (DND) undertook the task of disposing of some of its surplus infrastructure. Included in this program, was the disposal of the Tracadie Range, an 18,000 hectare (44,500 acres) parcel of land located in north-eastern New Brunswick, Canada. Starting in 1940 until the suspension of all military activities in 1994, the range was developed for a number of purposes namely as an artillery, mortar, air to ground and air defence battery training area. It was estimated inspite of the absence of records prior to 1969, that close to two million rounds of numerous nature had been fired with a potential unexploded ordnance (UXO) count of 400,000.

Throughout the existence of the range, access by the general public was allowed but controlled by DND because of the presence of out-of-bounds danger/impact areas which covered approximately 20% of the property. Numerous activities such as blueberry cultivation harvesting, forestry operations, fishing and hunting were common practice and coordinated in order not to interfere with on-going military training. The

economical advantages offered by the Tracadie Range resources had always been considered as an important issue by the local community as well as the provincial government. The range closure was interpreted as an opportunity to exploit these resources to their fullest potential. Therefore, following the announcement by DND to dispose of the range property, the Province of New Brunswick expressed an interest in acquiring the land to develop it for numerous public uses.

DND STRATEGY FOR LAND DISPOSAL

Because of the inherent danger associated with previous military operations at the Tracadie Range, public access could not be allowed on the whole property. Furthermore, in order for DND to be confident that the degree of risk associated with the land transfer is minimized, it was necessary to acquire good knowledge of the UXO contamination beyond any previous survey work conducted in the past.

In order to determine what was practical and affordable with respect to UXO clean-up of the Tracadie Range, it was necessary to conduct an initial UXO range survey. Based on the survey findings and recommendations, a plan of action with respect to the feasibility of range clearance operations and subsequent opening of areas declared safe to the public would be determined.

Two important criteria dictated the strategy on how to conduct the UXO survey/clearance work prior to disposal of the land to the subsequent user. They were:

- The extent and level of UXO contamination; and

- The interest expressed in the land.

Although poor historical records prior to 1969 have prevented a precise evaluation of the extent of some of the impact/target areas, preliminary visual investigations by DND have allowed the development of a map showing zones of likely UXO concentrations covering the low, medium and high ranges. The information from the visual investigation, although sketchy in nature, provided part one of a framework for prioritization of the survey/clearance work ahead.

Based on the non-military uses of the range during all the years it was in operation, DND became aware of the potential follow-on uses for which significant interest might be expressed. The range has been used extensively for blueberry cultivation and forestry operation, both of which are thriving economic activities in this area.

Other parcels of land within the range have been identified for other public uses. These areas which have been identified as having an immediate follow-on use potential made up part two of the framework for prioritization of the survey/clearance work that lay ahead.

UXO SURVEY CONTRACT

To complete the Tracadie Range UXO survey, DND awarded in April 1995 a contract to Dillon/ADI for $2.8 million. The main objectives of the Statement of Work were:

- Determine the extent of contamination by conducting a UXO survey encompassing both historical search and field work;

- Develop suitable options for range clearance operations;

- Prepare estimated budgets and schedules for the proposed range clearance operations, and

- Prioritize assessment of those areas of the range most likely to be free of UXO and for which a high interest has been expressed such that these areas can be made available as soon as possible.

In order to meet the objectives stated above, the contractor needed to cover with his survey equipment a minimum of 2.5% of the total range area in order to delineate precisely the extent of the impact/danger areas. Once these have been identified, the contractor proceeded by covering a minimum of 12.5% of the impact/danger areas. The procedure had been the general policy within DND for previous range surveys and was also applied in this case. Although there are no specific guidelines for the conduct of UXO surveys, it is felt that the 2.5% and 12.5% surveys combine good confidence with reasonable cost.

The contractor was provided with DND priorities for survey work which were established as either low, medium or high. As mentioned before, these were based on previous knowledge on the level of UXO contamination as well as the significant interest expressed for the different land parcels inside the range property.

Another important aspect of the survey contract was to establish precisely what would be the different potential future uses for the land, as they would have a definite influence on the clean-up requirements. Follow-on use

requirements constituted the basis for a risk-based approach to the clean-up of the Tracadie Range. By adopting this approach, DND shifted its requirements from the generic range clean-up to a site specific range clean-up. In the generic case, it is specified that ranges have to be cleaned up according to one of the three following levels.

- Level I, in which only the visible UXO items at the surface are removed. It involves no digging.

- Level II, where the UXO items are removed to a depth of 45 cm (18 inches); and

- Level III, where the UXO items are removed to a depth greater than 45 cm (18 inches) to meet the safety requirements imposed by the future use.

By identifying the different areas of the range targeted for follow-on uses, it would be possible to adapt a range clearance scenario to the proposed future use thus providing the opportunity to realize a cost efficient clean-up while providing assurance that the risk to the public would be minimized. There was also the need for DND to identify potential areas which for monetary reasons could not be economically cleaned up to meet specific follow-on use scenarios. Thus the subsequent users had to be made aware of DND's intention to dispose of the Tracadie Range did not mean that the whole property would be cleaned up to a level that would guarantee a specific use or even follow-on use.

THE DISPOSAL PROCESS

It is DND's intention in the summer of 1996 to dispose of parts of the Tracadie Range for which no or very low levels of UXO are expected. Negotiations for the transfer process will start with the Province of New Brunswick in early Spring 1996. For that purpose, two working groups made up of representatives of DND and the Province will be set up by identifying the intervening parties who would have a vested interest in the seven major issued identified for discussion. These are:

- Clean-up standards, which will have to be adapted to the future adjacent land uses in order to conform to the philosophy behind the risk-based approach. The possibility exists for soil contamination as a result of residual energetic materials being deposited in the soil after explosion of the ordnance or leaching into the ground following corrosion of the UXO. Also the presence of large quantities of rubbish, as a result of non-military activities will have to be addressed as an issue in the negotiations.

- Costs, which will dictate the extent of the clean-up. Use of the risk-based approach will result in cost efficient clean ups but will not guarantee that the whole property will be cleared on UXO in areas of extremely high UXO levels.

- Future land uses are an integral part of the risk-based approach and will dictate the clean up standards. These would have to be integrated into property transfer documentation to ensure the specified future uses will indeed take place.

- Liability might become a contentious issue insofar as a range parcel previously contaminated with UXO is to be transferred to a subsequent user. Depending on future uses, some areas might only receive a Level I clean up, with others being cleared to a Level II requirement. Only a Level III clearance would permit DND to categorically state that a parcel of land was free of UXO. In all other cases, DND can only state what steps it has taken to ensure that the property is available for specific follow-on uses. In some cases, portions of the property may never be available for any follow-on use, in which case it is hoped that they could be classified as nature preserves.

- Security has been provided by DND while the range was being used by military personnel. With the transfer of land parcels to the Province of New Brunswick as they are being declared safe, the requirements for DND to provide security will be reduced accordingly whereas the future owner of the land will be required to provide security to ensure that the public does not wander about on adjacent parcels of land that are unsafe.

- Transfer procedures will have to be established in an efficient manner to allow for a rapid transfer of land to the Province of New Brunswick, which wants to benefit from the many socio-economic advantages offered by the Tracadie Range. A quick and efficient transfer will also mean early cost savings for DND as responsibility for property management is transferred to the Province. This must not however, be conducted at the expense of public safety.

- Timing will be influenced by many if not all of the above issues and drives the whole land transfer process. The Province has clearly expressed its interest in acquiring the range as quickly as possible and DND also wants to dispose of the property in a timely manner.

The Tracadie Range land transfer process has allowed DND to use new procedures leading to the decommissioning of the Tracadie Range. These are:

- Innovative survey procedures which have proven more efficient in assessing the level of UXO contamination;

- A risk-based approach to range clearance to reflect follow-on uses; and

- The formation of working groups to include all intervening parties who could influence the land transfer process based on major issues associated with this process.

HOW SAFE IS SAFE?

Although DND is committed to cleaning up the Tracadie Range, there cannot be a full guarantee that the property is free of UXO. The level of risk can be minimized is a specific type of clean-up if associated with a specific follow-on use. However, the inherent level of risk associated with each cleared parcel will vary from high to low as the clearance varies from a Level I to a Level III. Good balance must be found between the level of risk and the level of clean-up, otherwise if only zero risk is considered acceptable, the whole range property will become a "no man's land". This would defeat the purpose for which the land transfer process has been undertaken in the first place and would require DND to provide security and access control for an indefinite period of time. This would be an unsatisfactory solution for DND and for the communities surrounding the range.

ASSESSMENT METHODOLOGY

The purpose of the unexploded ordnance survey of the Tracadie Range is to establish a strategy for the clearance of UXO contamination in order that it may support subsequent land use. To this end specific constituent objectives have been established. These objectives were as follows:

• To understand the history of military related activities at the range and the nature and location of UXO which is likely to be present.

• To reliably characterize and locate the UXO contamination boundaries throughout the entire range.

• To understand the potential and likeliest uses and activities which will occur on the land after it is turned over by DND.

• To assess clearance alternatives and recommend a specific clearance strategy which includes clearance for specific areas of the range corresponding to the potential subsequent land uses and activities in the area.

• To assess the potential environmental effects of clearance alternatives and make recommendations for the management of those environmental efforts.

While each of these objectives are key to an accurate assessment and the development of clearance strategies, the innovative aspects of the assessment have been the strategies developed to determining the extent and boundaries of likely UXO contamination.

DETERMINING THE EXTENT AND BOUNDARIES OF UXO CONTAMINATION

Historical research undertaken of both documentary and anecdotal sources contributed a description of past military use which enabled a prioritization of areas for investigations, based upon an assessment of those areas unlikely to contain UXO which would therefore likely be suitable for early release with no or minimal clearance costs. However, information from these sources was incomplete and often in conflict and no confidence could be had that all likely impact areas and disposal locations were known.

DND's initial concept for the assessment of the Tracadie Range relied upon determining the likely impact areas from their historical research. Following this determination electronic detection and intrusive investigation of the impact areas and surrounds would be undertaken at the sample rates referred to earlier. Using this strategy, a maximum of 52% of the total range area would be sampled and investigated. It was obvious that with sparse historical records no confidence could be achieved that the remainder of the range area did not contain unidentified impact areas.

To address this potential problem it was proposed that a strategy which utilized the rapid electronic data collection capabilities and flexibility of the TM-4 magnetometer system be applied to the total range area. This strategy from which clearance strategies and budgets could be developed for the Tracadie Range, involved three electronic survey components which were applied to various sectors of the range ranked in priority for assessment, based on the above discussed likely availability for early release. The three component assessment was then applied sequentially to each of these

sectors. The first stage consisted of systematically mapping and statistically analyzing regularly spaced magnetometer transects covering the entire range. The purpose of this was to identify the number and concentration of ferrous items using a uniform sample density across the range. This operation was aimed at identifying areas of ferrous contamination which could represent target impact zones or disposal localities.

INITIAL SAMPLE SURVEY

This initial survey involved the collection of digital, high definition magnetic data using the TM-4 magnetometer system. The data was collected by walking the TM-4 along north-south transect at the desired interval between transects to provide the specified sample areas. Total magnetic field readings were taken at 8 inch interval along each transect. The transects were walked between survey control lines which were established in east-west directions at approximately 500 metre (1640 feet) intervals across the entire site. The only preparation required for the survey was the cutting and marking of the survey control lines which occurred prior to the electronic survey.

Electronic data collected during survey operations was processed to generate a data set, over the site, representing the variation in the diversity of magnetic items and to provide a representation of the magnetic background noise. During data processing raw magnetometer line data was converted into a positioned data set that digitally represents the magnetic field over the entire site. In addition, the data processing stage involves the removal of temporal variations in the magnetic field, data validation, filtering and the editing of operator notes made electronically during the data collection operation.

Following processing, the electronic data is output in several forms which are used in the interpretation stage. All these outputs can be to a desired scale and are referenced to the necessary coordinate system. These outputs include:

- Annotated magnetic profiles which are scaled, plan format representations of the line data.

- Ferrous density contour maps which represent the primary results from data processing and show the ferrous items as a number of ferrous items per hectare/acre.

- Color image of ferrous density also representing a count of ferrous items per hectare/acre using color variations. An example of this is attached as a figure.

- Color image of background noise threshold. This is used to determine the confidence of detecting various items in specific areas of the range. An example of this is attached as a figure.

- Field annotation. These show notes and comments entered into the TM-4 during data collection. These may be observed items, geological features or significant events.

During the interpretation/analysis of the data, contour and color images representing the density of ferrous items per acre were first used to identify the pattern of low, medium and high levels of ferrous items. Each density level was examined separately and systematically. During this process consideration was given to operator notes, road and stream systems, ammunition related discoveries, geological features, calibration and validation data and the results of historical research.

As a result of this initial electronic survey, analysis and interpretation, it has been possible to identify those areas where the extent of ferrous contamination is high or medium and could, therefore, represent potential impact areas. Even more importantly it is possible to offer confirmation that other areas are unlikely to contain UXO or ammunition related contamination.

Having identified areas of potential UXO contamination the next two stages of electronic survey are designed to define the boundaries of contaminated areas, determine the likely concentration of UXO and identify the types of UXO present.

Areas identified during the initial sample survey as unlikely to contain UXO were also subjected calibration and validation surveys, discussed below. The purpose of these surveys were to verify the extent of ferrous contamination and to confirm that ammunition related items were unlikely to be located within these areas.

DETAILED SAMPLE SURVEY

The second stage of the electronic survey was also carried out using the TM-4 digital high definition magnetometer system. During this survey the magnetic readings were sampled at higher rate, in the case of the Tracadie Range the sample rate was increased five times. The increased sample was achieved along transects separated by shorter

distances. The output and analysis process used for this survey were similar to those outlined in the initial survey.

Areas of the range subject to the detailed sample survey were areas which the initial survey identified as containing concentrations of medium and high ferrous items which could not be explained or which were suspected of being impact areas. The detailed surveys are aimed at better defining the boundaries of likely impact areas and at identifying areas to be subjected to the third stage of the electronic survey the calibration and validation survey.

CALIBRATION AND VALIDATION SURVEYS

Calibration and validation electronic surveys formed the third component of the survey methodology applied to the Tracadie Range. The objectives of these surveys were to:

- Assess the extent of UXO contamination in representative areas by physically examining all ferrous anomalies in the calibration and validation grids;

- Determine the ratio of UXO to non hazardous ferrous items; and,

- Identify UXO type and potential hazard.

Calibration and validation surveys have been and will continue to be carried out over 50 metre (160 feet) by 50 metre (160 feet) representative sites (grids) throughout the survey area. These calibration and validations grids were selected and located to be representative of the characteristic electronic line data outputs identified through the survey areas. These sites included areas where ferrous anomalies were characterized as low, medium and dense. Additionally, the selection of calibration and validation sites took into consideration:

- Observed ordnance;
- Impact areas identified by the Stage I historical studies;
- Representativeness;
- Vegetation cover (i.e., the need to limit environmental impact);
- Geological features (such as marsh areas, with a higher background magnetic signature); and,
- Ease of access.

Each calibration and validation grid is subjected to a detailed electronic survey using the TM-4 magnetometer system operated in the hand carried mode. Electronic data is collected along parallel transects, usually in a north-south direction, at one metre (3 foot) intervals. Total magnetic field readings are taken at 20 cm (8 inch) intervals along each transect. The collected electronic data is processed and interpreted using interactive computer software and each ferrous anomaly above the background threshold magnetic noise is identified and documented in an Interpretation and Excavation Report. All identified anomalies are then investigated by an EOD team and subsequently the site is resurveyed to confirm that all previously identified anomalies have been investigated and where possible removed.

The preparation of calibration and validation grids required that the four corners of the 50 metre (160 feet) x 50 metre (160) feet areas be pegged, clearly marked and their coordinates to the national grid recorded. The grids have to be sufficiently clear of vegetation to allow unhindered walking in straight lines between line markers.

While environmental factors are a consideration in the selection of the calibration and validation grids, it is not always possible to identify a location that required little or no vegetation that also meets the other selection requirements. Consequently, some vegetation clearance was necessary on most grids. Clearance was usually restricted to scrub, sapling and dead fall, while large/mature trees were not removed.

RESULTS

The electronic survey of the Tracadie Range is continuing and is scheduled for completion in December 1996 with reporting due to be completed by February 1997. Notwithstanding this, the electronic survey has produced some significant findings which are being acted upon to accommodate current demands on the land. The first season of electronic survey operations were undertaken in areas which were identified as potential for early release, requiring minimal or no clearance. The survey has in general confirmed this initial assessment. However, it did identify a previously unrecorded impact area and it has defined the boundaries of areas which are unlikely to be contaminated by UXO or ammunition related items.

The electronic survey, to date, identified wide spread ferrous anomalies throughout the site, however, the concentrations of these anomalies have for the most part been low, 0 to 3 items per acre. Calibration and validation surveys have identified anomalies in these suspected low likely UXO areas as being related to camping, hunting and forestry activities while

concentrations of domestic garbage have been identified along most roads and tracks in the range.

As a result of these findings approximately 13000 acres have been identified for immediate release and clearance. Recommendations and budgets for the clearance of a further 7000 acres which could be made available for release in the next two years have also been made.

OTHER ELEMENTS

While the electronic surveys utilizing the TM-4 and its accompanying specifically designed software have been key elements in the rapid and thorough assessment of the Tracadie Range it has not been the only factor influencing the development of a total clearance strategy.

Community liaison and stakeholder consultation have been a significant component of the project from the outset. These have been key to likely future use scenarios and have taken the form of public meeting, interviews with influential and knowledgeable figures in the community, a 24 hour public information line and discussions with local, regional and provincial authorities. This process will continue up to the final release of the land. A partnering process has been established to gain local and provincial acceptance of clearance plans and to facilitate the final hand over of range lands.

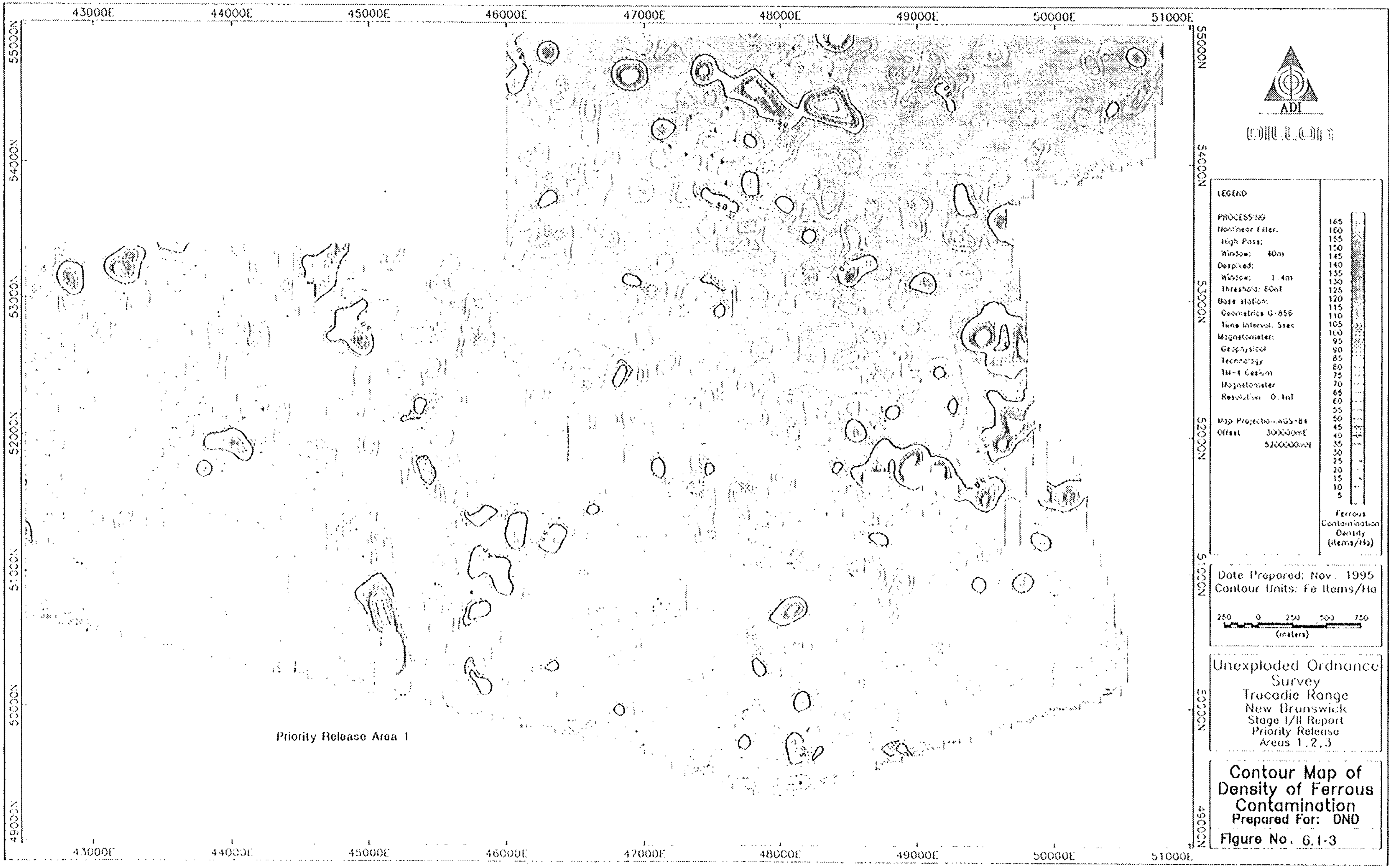
Environmental and archaeological factors were also assessment considerations. The range is cut through the middle in an east-west direction by the Big Tracadie River which is known to be a major east coast salmon river. Additionally during the course of the assessment the river was also found to be of significant archaeological importance with much evidence of prehistoric habitation, principally, in the form of stone artifacts being located. An environmental screening which considered the potential environmental effects of the various clearance options was undertaken. This environmental screening was used to:

- examine the project in terms of its environmental significant elements or potential events;
- describe the existing environmental condition in the study area;
- identify the potential interaction between the project and the environment;
- identify opportunities for the avoidance, prevention, mitigation and management of adverse effects, and
- provide summary of the significance of potential adverse effects.

CONCLUSION

The Tracadie Range UXO survey project constitutes an important part of the decommissioning process undertaken following the range closure in 1994. The UXO survey of the Tracadie Range has allowed DND to manage a project with an innovative electronic technology for conducting UXO surveys. It also provided a high level of confidence in the survey results and recommendations for clearance which followed. The UXO survey was also an integral part in the development of an innovative approach which hopefully will constitute a framework to range decommissioning across DND. By considering follow-on uses for the range property, it has been possible to adapt the recommendations for clearance to specific future uses. This constitutes the foundation for a risk-based approach to range clearance and will allow proper subsequent uses for the property by the public. Indeed, the level of confidence provided by the innovative survey technology will have a direct impact on the effectiveness of clearance scenarios chosen and will ensure that future uses are made possible with minimal risk to the users. Such an approach ensures that both DND's and the subsequent user's objectives are met.

With the advent of base closures and reductions in the past few years, the public is becoming more sensitized to the issue of follow-on uses for ex-military ranges. As the requirement by the public for surplus range properties grows, the importance of a risk-based approach to range clean ups cannot be over emphasized. However, there must be an acceptable level of risk to both the present military user and the subsequent public user. The acceptance in the level of risk involved can only be gained through confidence that the range property has been fully scrutinized at first and that appropriate clearance scenarios have been selected to meet the requirements of the follow-on uses.



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Priority Release Area 1
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PROCESSING
Nonlinear Filter:
High Pass:
Window: 40m
Despiked:
Window: 1.4m
Threshold: 60nT
Base station:
Geometrics G-856
Time interval: 5sec
Magnetometer:
Geophysical
Technology
TM-4 Cesium
Magnetometer
Resolution: 0.1nT
Map Projection: NAD-84
Offset 300000mE
5200000mN
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145
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5
Ferrous Contamination Density (Items/Ha)
Date Prepared: Nov. 1995
Contour Units: Fe Items/Ha
250 0 250 500 750
(meters)
Unexploded Ordnance Survey
Tracadie Range
New Brunswick
Stage I/II Report
Priority Release
Areas 1,2,3
Contour Map of Density of Ferrous Contamination
Prepared For: DND
Figure No. 6.1-3


Priority Release Area 1
49000N
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44000E
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48000E
49000E
50000E
51000E
ADI
LEGEND
Background Magnetic Noise (nT)
Date Prepared: Nov. 1995
Contour Units: nT
(meters)
Unexploded Ordnance Survey
Iracadie Range
New Brunswick
Stage I/II Report
Priority Release
Areas 1, 2, 3
Contour Map of Background Magnetic Noise
Prepared For: DND
Figure No. 6.1-4

DREDGING EAGLE RIVER FLATS
REMEDIATION STUDY IN AN ACTIVE IMPACT AREA

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ABSTRACT

Remediation in closed impact areas is hazardous because of the presence of unexploded ordnance (UXOs). Remediation of active impact areas compounds the problems due to the infusion of fresh UXOs. At Eagle River Flats, Alaska, massive waterfowl die-offs at the Army's impact area triggered an investigation as to the causes of mortality. With the discovery of white phosphorus from smoke rounds as the causal agent, a large, unprecedented multifaceted remedial investigation was initiated. Studies at the Flats can be categorized as either ecological assessments or remedial investigations. Ecological assessments considered the physical and biological dynamics of the Flats and the impact of these factors on the presence of white phosphorus and vice versa. Remedial investigations centered around either removal for treatment in a controlled environment or in-situ remediation or burial. Dredging is included in the first category. The objective of the experimental dredging project at Eagle River Flats is the removal of white phosphorus contaminated sediments from the Flats for treatment. The presence of UXOs and the quality of the environment are complicating factors. Dredging is selectively applied to those limited areas where white phosphorus is found, and conducted in such a manner as to minimize the environmental impact both while dredging and in the event of the detonation of a UXO. Specialized equipment obviously is needed to carry out this task. A small augerhead dredge was modified for remote control operation, using video feedback to the shore-based operator. The operator is stationed on shore in a hardened shelter that was tested by detonating a 105-mm HE round 35 m from the cab. Hydraulic fluid is vegetable based and nontoxic to prevent unacceptable pollution in case of spillage. Spoils from the dredging operation are pumped to a specially designed retention basin located on the nearby explosive ordnance disposal pad. The retention basin is used to decant supernatant from the spoils for eventual remediation of the sediment. For effective remediation and to lower the risk of a UXO detonating in the pump or along the spoils line, a method of excluding UXOs from the spoils stream is needed. After experimenting with several exclusion methods, a cutter and grate system was devised for the augerhead that successfully excluded UXOs while effectively processing sediment and vegetation. The study was successful enough that the remediation study for this superfund site has been moved to a removal action. The work is scheduled to be turned over to a private contractor for the 1996 deployment.

INTRODUCTION

Eagle River Flats is an estuarine salt marsh located on Ft. Richardson near Anchorage, Alaska (Fig. 1). For fifty years, it has been used as an impact area by both the Army and Air Force. During the 1980s, hundreds of dead and dying waterfowl were found in this area during spring and fall migrations. For five years, various state and federal agencies tried without success to unravel the mystery of this high mortality. Finally, in the spring of 1990, a group of researchers from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), working in conjunction with the Ft. Richardson Directorate of Public Works, Environmental, discovered the cause of these massive die-offs: white phosphorus (Racine et al. 1992).

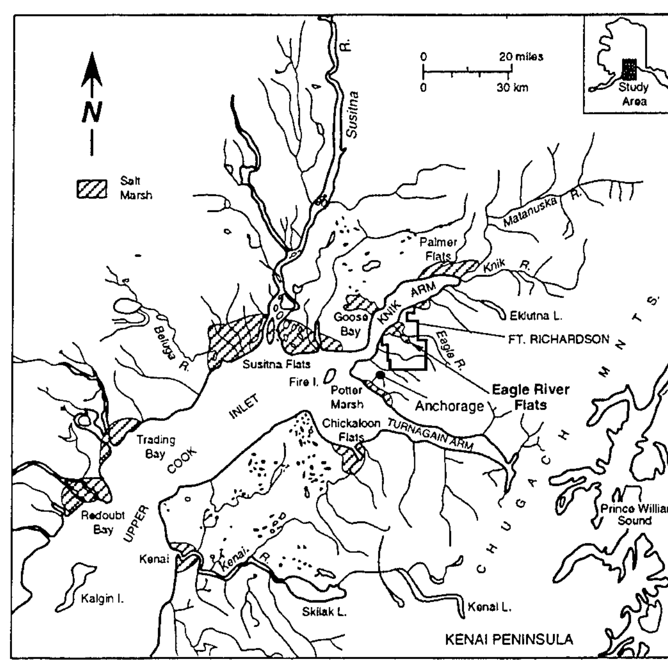

Figure 1: Eagle River Flats, Alaska.

White phosphorus (WP or P_4) is used by the Army at Ft. Richardson as a targeting and obscurant round. Because white phosphorus is extremely volatile in air, it was assumed that, upon detonation, all the white phosphorus would be consumed. However, evidence of the persistence of white phosphorus in the environment has previously been documented, most notably in Placentia Bay, Newfoundland, in 1968 (Idler 1969). The U.S.

military has also had experience with WP contamination of the environment. In the early 1970s, heavy rains resuspended white phosphorus in a settling basin, and subsequent overflow of the basin into a neighboring lake resulted in extensive fish kills (Sullivan et al. 1979). Although information was available as to the toxicity and persistence of white phosphorus, it was not widely known to be a problem. A previous study at the Flats (ESE 1990) in fact dismissed WP as a causal agent.

With the cause of the mortality identified, investigations were initiated to determine the biological and physical extent of the problem (Racine et al. 1992, 1993; Lawson and Brockett 1993). Additional studies were conducted into the persistence of WP (Walsh and Collins 1993, Walsh et al. 1995) as well as field screening methods for determining qualitative concentrations (Walsh et al. 1995). An analytical method for determining concentrations of white phosphorus in soils and water using gas chromatography has been developed at CRREL (U.S. EPA 1995, Walsh and Taylor 1993). Further work on a headspace solid-phase micro-extraction method is currently in process at CRREL.

The typical delivery method of white phosphorus to the environment at Eagle River Flats and other impact areas exacerbates the persistence problem. Due to cost considerations, ground impact fuzes are typically employed (Fig. 2). This tends to drive a significant portion of the WP into the ground (Walsh and Collins 1993). In cool, wet areas, this results in the failure to ignite or the extinguishing of WP particles. Without the ability to sublime and with a very low solubility in water (2.4 mg/L: Spanggord et al. 1985), the white phosphorus becomes quite stable and thus persistent. The result is continuing contamination in wetlands, especially ponded areas, which are extensively used by waterfowl.

At Eagle River Flats, waterfowl mortality is confined almost exclusively to a group known as dabblers. These are ducks and swans that typically feed by tipping down and feeding on seeds and vegetation found on the bottoms of ponded areas. The Eagle River and other rivers feeding into the Knik Arm of Cook Inlet are glacial in origin, and sediments tend to be fine. This sediment, also known as glacial flour, can be classified as a silt, with 95% finer than 0.1 mm (200 sieve). Lethal size particles of white phosphorus are close to the size of seeds and sprouts preferentially sieved from these fine sediments by the waterfowl. When WP is ingested, the birds go into convulsions and eventually die. Autopsies performed on these birds have occasionally resulted in smoking gizzards when they have been opened.

Figure 2: Detonation of WP round at Eagle River Flats.

REMEDIATION STUDIES

Remediation studies at Eagle River Flats were initiated in 1994. Two parallel strategies were pursued: removal and in-situ treatment or burial. The in-situ work is generally less intrusive than removal. This work ranges from enhancement of natural attenuation and draining of contiguous ponded areas to covering contaminated areas with geotextiles or bentonite-ballast mixtures (Racine and Cate 1994, 1995, in press). Each methodology is best applied to specific areas of contamination. Although successfully applied on a small scale at the Flats, none of these strategies can effectively remove white phosphorus from the environment in large, permanently ponded areas without extensively altering the environment.

Options for removal are limited due to the presence of unexploded ordnance and the instability of the sediment at the Flats. Dredging had been successfully used at Placentia Bay in their cleanup effort (Idler 1969) and was thus considered as an option for the Flats. Because this was a remediation study rather than a removal action, permitting for dredging in a wetland was simplified through the application of the U.S. Army Corps of Engineer's nationwide dredging permit. Natural attenuation studies (Racine and Cate 1995) indicated that in-situ remediation of the spoils is possible in a retention facility if the supernatant is decanted from the sediment and the sediment allowed to dry and warm. Thus a strategy for dredging in the Flats coalesced: using a small, remote-control dredge to dredge permanently ponded areas of the Flats, and pumping spoils to a retention basin where the excess water can be removed in a controlled fashion and the sediment allowed to dry. Natural remediation will remove the WP from the sediment.

SYSTEM DESIGN

Ponded areas at Eagle River Flats tend to be shallow (< 1 m), small (< 2 ha), and irregularly shaped. They are also critical to waterfowl as both feeding and loafing areas. The Flats are elevated due to the high tides in the area, in excess of 10 m between high and low tides. Therefore, a small dredge that can access contaminated areas without channeling is necessary.

The main factor in the dredge design after the ability to dredge the sediments is the presence of UXOs. The dredge needed to cope with the various munitions fired into the Flats over the years. For small munitions up to 40 mm rounds, an armored dredgehead

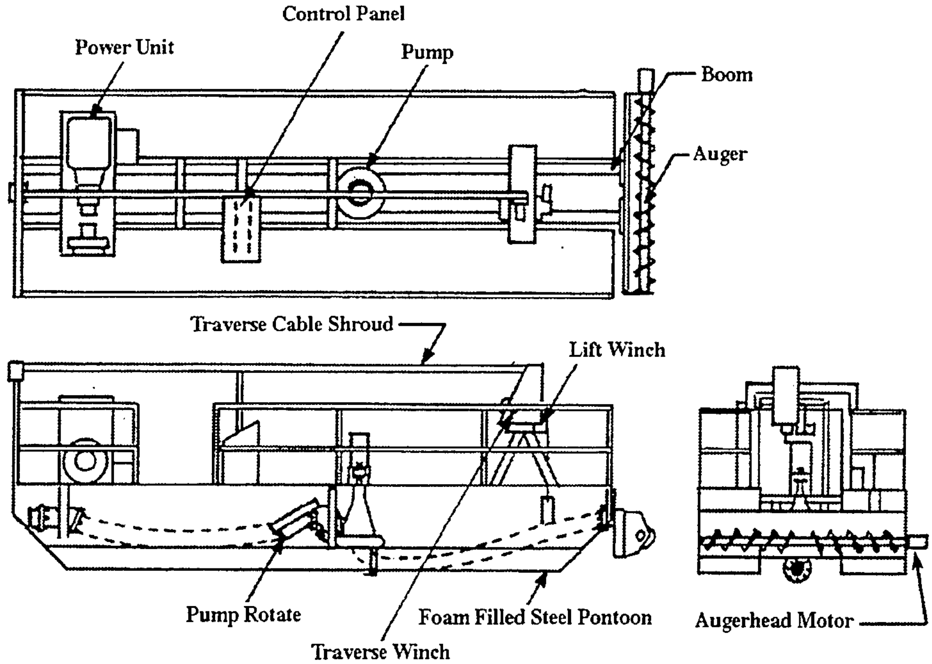

Figure 3: Dredge used at the Flats.

will minimize the impact of a detonation. For midsized rounds, 60-mm mortar to 105-mm howitzer rounds, placement of critical components such as the slurry pump and the power pack away from the dredgehead minimizes the damage to expensive systems in the case of a detonation. For the larger rounds found at the Flats, such as 500-lb bombs and 155-mm howitzer shells, the best that can be hoped for is to minimize the environmental damage in case of an explosion. For this reason, a shore-based power source and the use of nontoxic hydraulic fluid are necessary. And of course, the inherent dangers of operating in an impact area dictate that the operator be located off the dredge in a protected enclosure.

A modified augerhead dredge was leased for the Flats from ChemTrack Services Group, Inc., of Anchorage, Alaska (Fig. 3). An augerhead dredge was specified due to the nature of the contaminant. White phosphorus is easily resuspended in water, and settles slower than the sediments found at the Flats due to its lower specific gravity. The enclosed augerhead contains the sediment better during the dredging process, thereby reducing the recontamination of the dredged area. A cable-driven traverse system is the usual mobility method for this type of dredge and is employed on this equipment. The traverse system was anchored using one cubic meter concrete deadmen placed by helicopter. The use of spuds and lateral cables was considered but rejected on the basis of the danger involved in setting the spuds in the sediment of the Flats.

The slurry pump is located near the dredge center, 3 meters from the dredgehead. The electrohydraulic power pack, powered by a shore-based generator, is located at the back of the dredge as far from the dredgehead as possible. The pontoons are constructed of heavy gauge steel and foam filled to ensure floatation in the case of damage due to detonation of a UXO. The dredgehead shroud itself is constructed of 13-mm steel to contain the blast from a round. The top of the shroud is hinged to allow upward relief of any overpressure.

The dredge is controlled from a shore-based armored control cab (Fig. 4). This cab is constructed from 1.3 mm steel with 3.8-mm thick ballistic polycarbonate (Lexan) windows. The control cab was tested for integrity at the Flats by detonating two 105-mm HE rounds in different configurations at a distance of 35 m from the cab. The dredge was retrofitted with a pair of high-resolution black-and-white video cameras, linked to a radio fre-

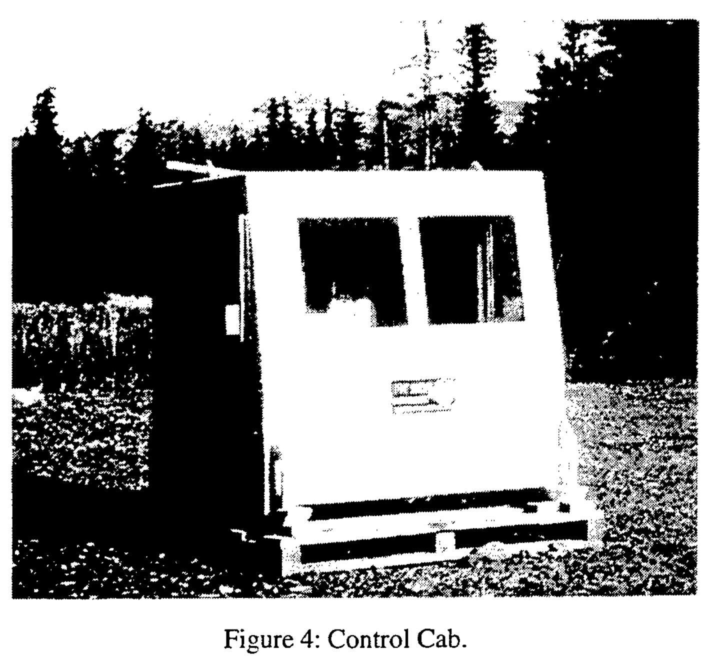

Figure 4: Control Cab.

Figure 5: Dredrge control monitor.

quency transmitter on the dredge. Overlaid on the image are the outputs of the pressure sensors on board the dredge: suction pressure (psia), outlet pressure (psi), slurry pump pressure (psi), and augerhead drive pressure (psi).

The slurry pump is a Cornell 6NHTA pump with a 6-in. (152-mm) inlet and a 14-in. (336-mm) impeller. It is driven by a 74.6-kW electrohydraulic power pack. Maximum power to the slurry pump circuit is 59 kW. The remaining functions, the traverse motor, augerhead motor, and pump lift cylinder, utilize a separate pump and have available the remaining 15 kW. Slurry pump, traverse motor, and augerhead motor flow controls are all proportional. Control is through an Allen-Bradley control (Fig. 5) located in the cab and wired to the dredge.

From the dredge, spoils flow through a 200-mm flexible rubber hose to shore. The hose, along with the power and control cables, are supported by polyethylene floats in the water. On shore, the hose transitions to a 250-mm polyethylene pipe for the 335-m trip to the retention basin.

The basin was constructed on the Explosive Ordnance Disposal (EOD) Pad using native and imported gravel (Fig. 6). The EOD Pad was a RCRA (Resource Conservation and Recovery Act) solid waste management unit (SWMU) at the time of the conception of the dredging program. Special precautions had to be taken to ensure that water pumped from the dredge would not percolate through the pad and mobilize any contaminants that may be beneath it. Working with the Corps of Engineers Alaska District office, a 0.8-ha retention basin structure was designed and built. Extensive testing of the pad and the basin were conducted, and with a 15-cm layer of compacted peaty silt lining the basin, percolation rates were low enough ($<10^{-5}$ cm/sec) to be accepted by the restoration program managers for use. At the far corner of the basin, away from the spoils inlet, a structure was built to control the decanting of the supernatant. This consists of an 8-m-long weir, a silt fence, and a 1.3-m-dia. drop inlet which leads to a 0.6-m dia. culvert out to the Flats. The basin was instrumented to monitor water level, sediment and air temperature, and sediment moisture as part of the remediation study.

DESIGNING FOR UXOs

In addition to the design modifications discussed in the previous section, a method for excluding UXOs was mandated by the 176th EOD Detachment based at Ft. Richardson. Several methods of exclusion were tried with mixed results before a cutter and grate system for debris exclusion at the dredgehead was developed and refined.

The first exclusion device implemented was a line expansion chamber between the dredgehead and the pump. The theory here was to greatly expand the area and thus decrease the flow between the dredgehead and pump to cause heavy objects such as UXOs to fall out. A spring-loaded trap door, which opened when the dredgehead was lifted out of the water, would dump any captured ordnance. The initial model, which we called a "boom box," was rectangular in shape and was not hydrodynamically designed. It was not very effective, but allowed limited dredging to be conducted at the end of the '94 field season.

At the start of the 1995 season, the old boom box was removed and a more refined model installed (Fig. 7). In addition to being hydrodynamically designed, a back-flushing system with spring-loaded side doors and a trap door on the inlet was incorporated to allow automatic cleaning of the box. An airtight hatch was also installed on the top to facilitate inspection.

This box worked quite well except for one factor: waterlogged wooden debris was distributed throughout the Flats. This material was of near-neutral buoyancy and thus did not fall out of the stream between the auger and pump. Upon reaching the pump eye, some pieces would jam in the inlet impeller, initiating a process termed "beaver damming" in which additional debris would accumulate until the suction side of the pump would starve for water and periodic cavitation would occur (Fig. 8).

Several tactics were tried to prevent ingestion of debris into the

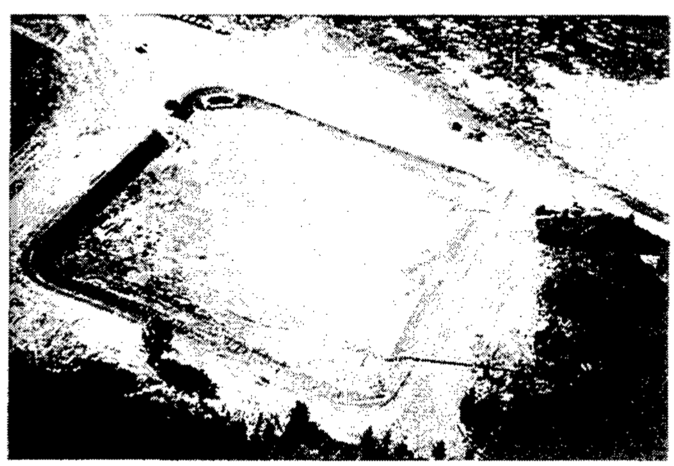

Figure 6: Spoils retention basin.

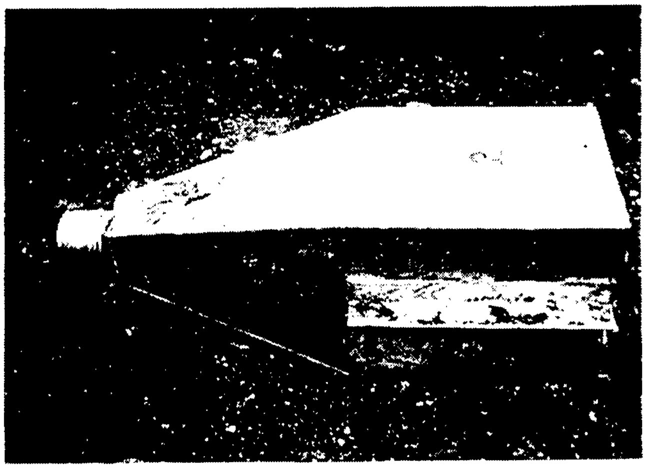

Figure 7: Ordnance capture box.

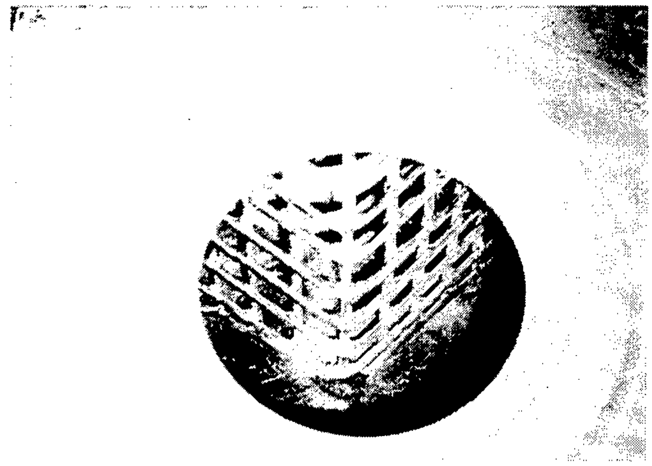

Figure 9a: Grating in boom box.

pump eye. Initially, a wire screen was mounted to the inlet on the augerhead shroud. This screen has 5-cm-square openings, which will exclude debris of the size that will clog the pump. Unfortunately, the tough vegetation found at the Flats quickly plugged the screen, and backflushing would not clear it. The screen had to be removed. A 5-cm screen was then installed inside the boom box, with the screening made of 1-cm-dia. bar to facilitate passage of vegetation and aid in backflushing Fig. 9a). Unfortunately, this strategy also failed, with the screen once again plugging after a short period of time (Fig. 9b). Some means of excluding UXOs and larger debris without impeding the processing of vegetation was needed that would be simple, reliable, and not require human intervention.

Investigations focused on two alternative methodologies: exclusion and maceration. Each has its shortcomings due to the mixture of debris and UXOs found at the Flats. Because of the presence of large quantities of metal fragments, pure maceration was ruled out as an option. Conversely, the presence of tough, stringy vegetation ruled out straight exclusion. A combination of the two approaches was needed.

The best place to exclude the debris is before it enters the dredge pump suction line. Although the screen proved to be a failure at this point, a grate with spacing a little less than the width of the most problematic material, dimension lumber, was installed. To clear entangling vegetation from the grates, a cutter was installed to sweep the grates, chopping any entangling vegetation and sweeping off any debris. In addition, long stiff tines were installed on the auger flights to premacerate the vegetation (Fig. 10). The auger motor was replaced with one with twice the torque but half the speed, so the power from the hydraulic circuit did not increase. With the grates in place, the boom box was no longer required and was removed. To ensure that no loss of flow would result from the grates, the open area of the grates was increased to 50% more than the original inlet. In addition, the inlet opening in the shroud was enlarged and a tapered transition box installed behind the shroud to adapt the rectangular opening to the 15-cm-dia pump suction line. Initial results using this new system were very encouraging.

Three modifications were made to the cutter and grate system to enhance its performance. First, the cutter and grates were beefed

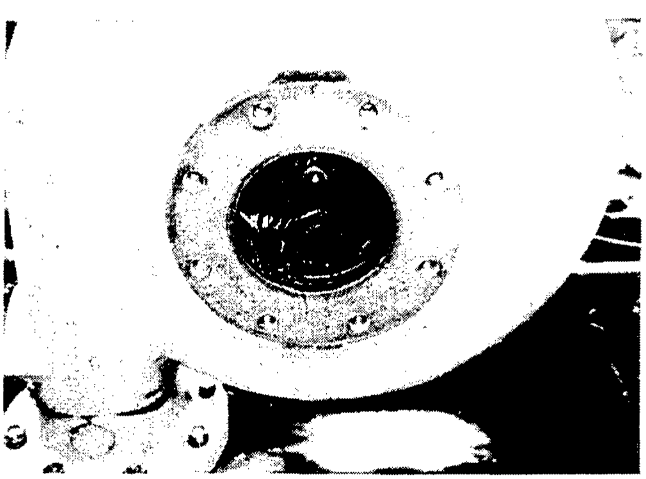

Figure 8: Blocked pump eye.

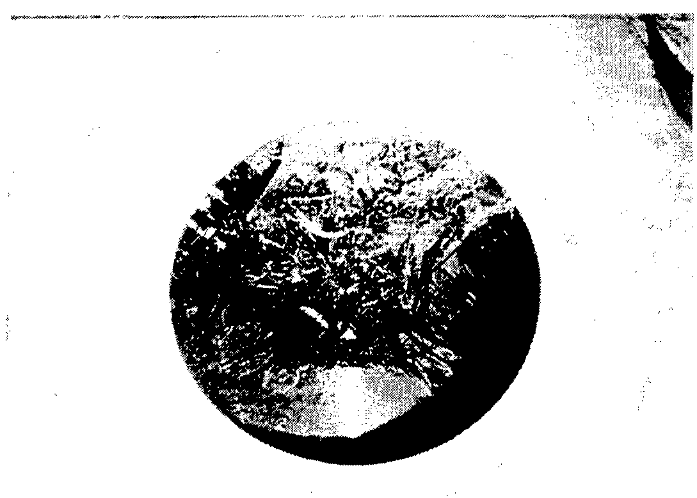

Figure 9b: Plugged grating in boom box.

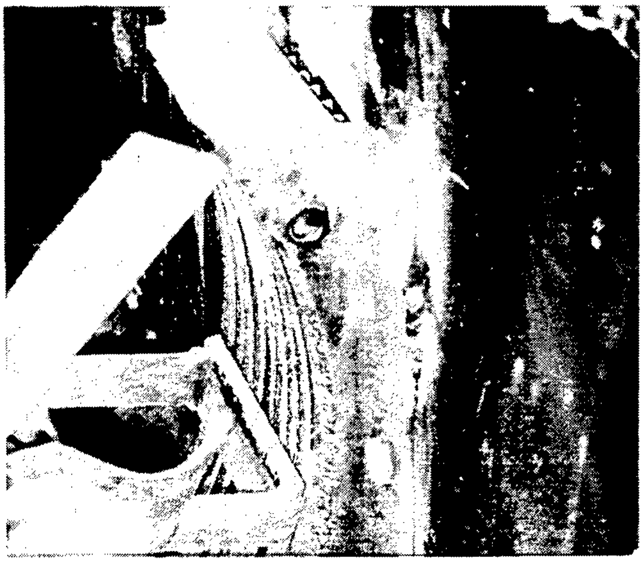

Figure 10: Cutter and grate system: first iteration.

up to better process the material. Some small material was lodging between the grates, so the grate shape was modified to a "T" shape with the wide side towards the cutter. This allowed small pieces of slightly oversized debris to pass through the grates.

The grates were also built into the shroud rather than mounting on the face, thus allowing for freer passage of material (Fig. 11). This required lengthening of the cutter arms. Finally, a cleanout door was installed on top of the transition box to allow the back side of the grates to be cleaned. This is necessary due to backflushing of processed vegetation and subsequent plugging of the grates. A sprung trap door on the bottom of the transition box allowed water to flow out in case the screen overly restricted the backflow of water.

Figure 11: Cutter and grate system: second iteration.

The new grate and cutter system was inspected by the Ft. Richardson EOD Detachment and met with their approval. System efficiency was greatly increased, with up to 24 hours of operation possible between maintenance shutdowns. The pump and inlet no longer caused delays, and we are now able to dredge in areas of low vegetation without significant problems. Highly vegetated areas are still problematic due to the thick vegetative root mat and tendency for these areas to accumulate debris. However, these areas are not generally sites of WP uptake for the waterfowl and thus need not be dredged.

DREDGING AT THE FLATS

The 1995 field season proved to be a test of perseverance for members of the field team. Prior to initiation of dredging, many other problems other than UXO exclusion had to be addressed. These ranged from faulty pipe connections to the wrong sized pump impeller. Each of the problems was addressed in turn. By the first week in September, a fully functioning system was in place.

Productive dredging commenced on 8 September. The area targeted for remediation is shown in Figure 12. This is a permanently ponded area known as Area C. Water depth ranges down to 0.5 m. Thus, the dredge must cut its own path. Large debris was pulled from the area and operations begun. Dredging continued through to the 25th, with interruptions caused by flooding and the loss of the access bridge to the site. Due to weather-related delays, the complete area was not addressed, although dredging was conducted in most of the areas targeted (Fig. 13).

During dredging operations, spoils were periodically sampled to determine contamination levels. Samples were taken from the spoils line near the retention basin outlet. The sampling device on the spoils line was located half way up the side of the pipe and projected a short distance into the pipe, perpendicular to the spoils flow. A total of four 4.2-L samples were taken every hour. After the sediment settled in the sampling bucket, the supernatant was decanted and a 500-mL composite sample obtained for later analysis for white phosphorus. A total of 137 sediment and 23 water samples were taken over the course of the summer.

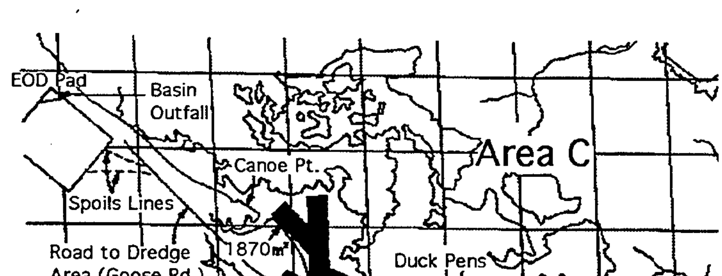

Figure 12: Area to be dredged at ERF.

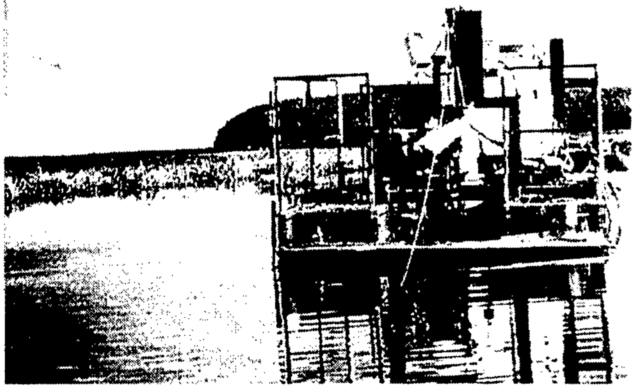

Figure 13: Dredge in Area C of Flats.

Results showed that 20% of the sediment and 4% of the water samples contained at least trace amounts of WP (Table 1). Data indicate that a sampling port directed lower and into to the stream flow will probably give higher, more accurate results.

Table 1: Chemical analysis of dredge samples.

	Sediment (Spoils)	Water (Supernatant)	Total
Number of Samples	137	23	160
WP Hits	26	1	27
% Hits	19%	4%	17%
Range (µg/kg)	0.22 - 66.00	-	-
Average (µg/kg)	6.16	4	-

Total area dredged was 2540 m^2. Average depth dredged was 1 m. Approximately 1,700 m^3 of contaminated sediment was removed from the area dredged. Using the 19% contamination rate and 6.16-µg/kg contamination concentration, enough white phosphorus was removed through dredging to kill over 1400 dabbling ducks (Table 2). The presence of the contaminated sediments in the retention basin had no observable effect on the wildlife attracted to the basin during dredging (Fig. 14: next page). Among the birds frequenting the basin during dredging operations were up to 60 yellowlegs and 24 American wigeon. No other dabbling ducks or swans were observed in the basin over the season.

Table 2: Contaminant removed as a function of lethal doses.

Species	Lethal Dose (mg)[1]	Single Species Mortality	Mortality Observed (%)	Multi-Species Mortality
Teal	1.5	2400	26	624
Mallard	4	900	37	333
Pintail	3	1200	37	444
Total		900-2400	100	1401

and Steele, and Sparling in Rachie and Cate (1985).

A rough economic analysis of the dredging operation in September indicates that although expensive, dredging is feasible. Factors such as the remote operation, the need for specialized equipment, necessary safety precautions, and environmental sensitivity all add to the cost of this operation and make it difficult to compare to other dredging activities.

A rough, maximum sustainable production rate based on our experience at the end of the 1995 season would be 500 square meters per day at a depth of one meter (water and sediment), based on a 10-hour day and about 60% run time. Actual transfer of sediment would be much lower, on the order of about 50% of this volume (due to "overburden" of water and overlap of dredging passes). Dredging would occur four days per week, and one day per week would be devoted to maintenance and positioning of the dredge. Drainage of the Retention Basin would occur during nondredging days. Estimated dredging time for a 0.4-ha site would be about 10 days. Table 3 gives a breakdown of estimated costs for a removal action based on a 0.4-ha (1-acre) area cleaned to a depth of about 1 m. Around two weeks will be required for actual dredging operations for this area. Labor costs are based on 10 hour days and six day weeks. A 30% pay premium is added for Alaska employees, and a 25% hazardous duty premium is added to that for working in an active artillery impact area. An estimate of the cost of an additional 0.4 ha is included in the table.

Other factors or scenarios not presented here will affect the economics of this strategy. The greatest is the lease cost of the dredge. This currently stands at $180,000 per year (1 August to 31 July). Whether the work is done by CRREL or an outside contractor, this cost will have to be factored in. The number of deadmen required to anchor the traverse system will also greatly affect cost due to the expense of placing them with U.S. Army Blackhawk helicopters. For a 0.8-ha area, the cost can vary from $215,000 to $240,000, depending on the need for helicopter time, personnel, and heavy equipment.

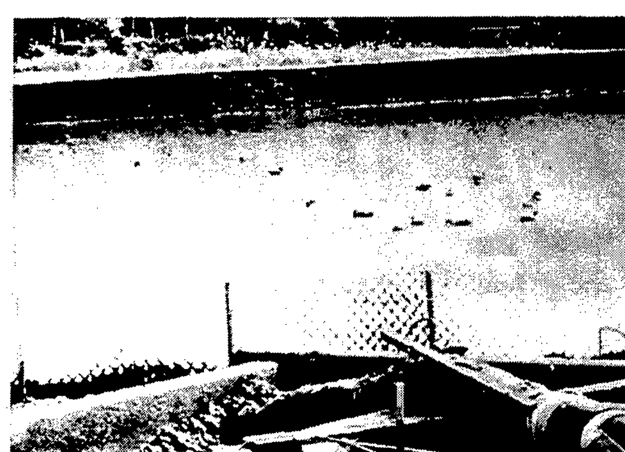

Figure 14: Wigeon in basin during dredging.

Table 3: Economic analysis of a 0.4-ha dredging operation.

		Heavy Equipment			Helicopter Support		Sample
Operation	Labor	Crane	Forks	Flatbed	UH-1H	UH-60	Analysis
Setup	$ 6,485	$ 1,040	$ 1,360	$ 1,040	$ 2,400	-	-
Dredging (1)	$ 10,514	-	-	-	$ 2,400	-	-
Sampling (2)	$ 6,455	-	-	-	-	-	$ 5,805
Retrograde	$ 3,242	$ 1,040	$ 1,360	$ 1,040	$ 2,400	-	-
Deadmen (3)	$ 1,414	-	-	-	-	$ 10,400	-
Subtotals	$ 28,110	$ 2,080	$ 2,720	$ 2,080	$ 7,200	$ 10,400	$ 5,805

Total per 0.4 ha, one deadmen set-up: $ 58,395
Additional 0.4 ha: $ 25,174

(1) Labor rate based on a WG-11/5 with a 30% AK differential and a 25% haz. duty premium.
(2) Labor rate based on a GS-13/5 with a 30% AK differential and a 25% haz. duty premium.
(3) Crew of 4, 4 hours

SUMMARY

Dredging an area containing unexploded ordnance presents obvious problems. At Eagle River Flats, Alaska, the objective was remediation of the sediments contaminated by exploded ordnance. As this area continues to be used as an impact range by the U.S. Army, retrieval of UXOs was not necessary, nor was it desirable. Therefore, a remediation method that excluded UXOs while removing the contaminated sediments surrounding them was necessary.

Small scale dredging was the methodology chosen. Due to the dangers to personnel and equipment, the dredge was modified for remote control operation from a hardened shore-based control cab. Video feedback, including readouts from various pressure sensors aboard the dredge, allowed effective operation of the equipment. The use of a shore-based generator, nontoxic hydraulic fluid, and design modifications to the dredge were implemented to minimize damage in the case of detonation of various classifications of UXOs.

The cutter-grate system designed for the dredgehead proved quite effective in excluding both UXOs and other debris from the dredge pump. During the course of dredging an area of over 2,500 m^2 to a depth of 1 m, no detonations occurred. Recovery of ordnance was not the objective of this investigation, and no attempt was made to collect any UXOs that may have been processed by the augerhead. Areas dredged were cordoned off to ensure no accidental detonations.

A rough cost analysis for the removal and treatment of the spoils in the specially constructed retention basin indicated that the process was feasible although not inexpensive. The difficult environment and presence of UXOs required special precautions as well as specialized equipment. Operating this equipment remotely resulted in inefficiencies that would not otherwise be encountered, and deployment is more difficult due to the use of shore-based power. The final system employed at the Flats, although perhaps not ideal, was quite capable of meeting the original objectives of the task: the removal of white phosphorus from the environment with as little damage to that environment and the least risk to personnel.

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TIME DOMAIN ELECTROMAGNETIC METAL DETECTORS

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INTRODUCTION

Two preceding presentations in this conference deal with time domain electromagnetic (TDEM) systems for buried metal detection: a presentation by J. McNeill of Geonics, Ltd.; and one by Peter Kaczkowski of the University of Washington. To avoid duplication this presentation will focus on illustrating by case histories the range of applications and limitations undoubtedly stressed by the previous presenters. Advantages claimed for TDEM metal detectors are:

1. Independence of instrument response (Geonics EM61) to surrounding soil and rock type.
2. Simple anomaly shape.
3. Mitigation of interference by ambient electromagnetic noise.
4. Responsive to both ferrous and non-ferrous metallic targets.

The data in all case histories to be presented were acquired with the Geonics EM61 TDEM system.

CASE HISTORY

Case History 1: Test Bed Site on Molokai, Hawaii

Ogden Environmental Services Co. prepared a test bed with inert ordnance to evaluate the capabilities of various subcontractors to detect ordnance buried over volcanic terrain typical of the Hawaiian Islands with an eye to the large remediation efforts forthcoming for Kaho'olawe. Volcanic terrain presents two unique difficulties to buried metal detection. These are:

1. Large variation in magnetic susceptibility can cause high noise in magnetic sensor.
2. The often rough surface can cause high noise in sensors sensitive to change in height above surface.

Figure 1 shows the color contour map of the electromotive force (EMF) measured by the Geonics EM61. The data were acquired at 3 foot line spacing, and with recording intervals along the lines of about 0.6 feet. Superimposed on Figure 1 are the UXO targets seeded in the test bed, and **Table 1 contains information about the ordnance and depth of burial.** Also listed in Table 1 is the signal/noise ratio of the each anomaly. The site was at the perimeter of a Navy bombing range and anomalies found in addition to the seeded targets are exploded ordnance waste. This case history illustrates critical characteristics of the Geonics EM61 TDEM metal detector. They are:

- All seeded targets were detected with a signal-to-noise ratio in excess of 2.1 and or high as 11.3.
- The anomalies over isolated targets are simple bell shaped. This greatly facilitates development of automated picking algorithms and neural network approaches.

Case History 2: Fort Monroe, Virginia

Fort Monroe dates as a military facility from 1609, and the dominant objective was to locate pre-Civil War cannon balls and ordnance of a later origin.

Figure 2 shows a color contour map of the EMF measured with the Geonics EM61 over a section of Fort Monroe. The data were acquired with the EM61 in a wheel mode at 5 foot line spacing and about 0.6 feet recording interval along the line. This work was performed by Blackhawk Geosciences as a subcontractor to Parsons Engineering. For this work, the northern and easting of the anomaly center was picked by an automatic picking routine with a cursor on the computer screen. Again, this case history illustrates several of the advantages of a TDEM sensor.

1. The response of the surrounding soil is very low, showing the near independence of the sensor to soil and rock types.
2. The buried utility is identified by its linear trend.
3. Simple anomaly shape of isolated targets.
4. Some anomalies were dug up and some were ferrous (cannon balls), others were non-ferrous (a British riding stirrup).

Case History 3: USDOE - Rocky Flats Plant

This case history is not related to UXO detection, but was selected to illustrate the mitigation of instrument response to ambient electromagnetic noise. The objective of this survey

was to locate waste in metallic containers buried in a trench that mainly contains ash. For several years, we were unsuccessful in locating metallic targets at this location with ground penetrating radar, magnetic, and frequency domain electromagnetic sensors. The reasons for this was that the trench ran near parallel and under a high voltage power line causing high noise in magnetic and frequency domain (Geonics EM31) sensors. The area was re-surveyed with the Geonics EM61 TDEM system, and the response was virtually not influenced by ambient noise.

Figure 3 compares contour maps of the EMF measured with the Geonics EM61 and total magnetic field measured with magnetic sensors. The EM61 detector allows clear anomaly detection under the high voltage power lines.

The ability to effectively perform surveys in high ambient noise environments is an important one. Urban developments have encroached on former defense sites, e.g., at Fort Monroe, surveys were performed between base housing with overhead and underground 60-cycle power lines, and clean-up other bases will require also working in high ambient noise environments.

SUMMARY

The TDEM metal detector has proven effective for detection of buried metallic targets. The advantages previously listed for the instruments have clearly been realized in the field. The present limitations of this technology are:

- Discrimination capabilities in terms of type of ordnance, and depth of burial is limited.
- Ability of resolving targets with small metallic ambient needs to be improved.

The direction for making improvements in the technology are evident (some are discussed in a previous paper by J. McNeill) and within present capabilities. Adding additional time gates will assist discrimination, and so will developments of neural network approaches (Lavely this conference).

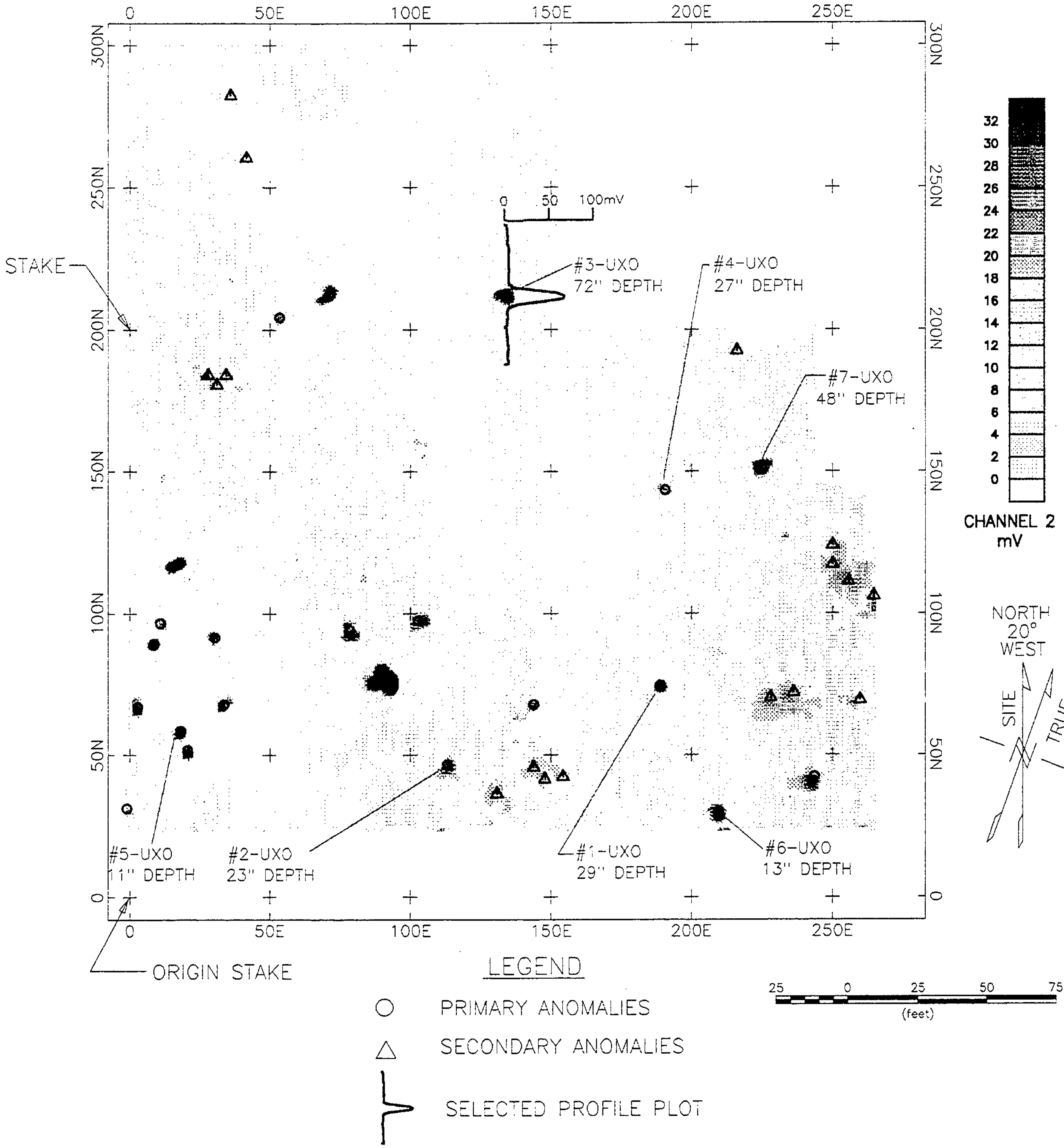

Figure 1.
Contour map of electromotive force measurement with Geonics EM61 (channel 2) over test bed of Ogden Environmental, Inc. on Molokai, HI. All seeded anomalies were detected, and the numbering of each anomaly is superimposed on the figure. Table 1 provides specifics on each anomaly.

Table 1
Type, depth of burial, location, and signal to noise ratio with Geonics EM61 (channel 2) of seeded anomalies in Ogden Environmental, Inc. on Molokai, Hawaii

UXO DESCRIPTION	*DEPTH*	*EASTING*	*NORTHING*	*mV*	*S/N RATIO*
#1 - MK-1 ROCKET WH	29"	188.9	74.6	81.4	7.4
#2 MK-76 PRACT. BOMB	23"	113.2	46.6	31.2	2.7
#3 - 5" RKT. WH	72"	134.2	212.0	73.4	8.0
#4 - 2.75" RKT. WH	27"	190.5	143.3	23.8	2.1
#5 3.5" RKT. WH	11"	18.2	58.5	45.1	6.5
#6 - 81mm MORTAR	13"	209.8	29.7	59.1	4.9
#7 - 105mm ARTILLERY	48"	225.1	150.9	129.2	11.3

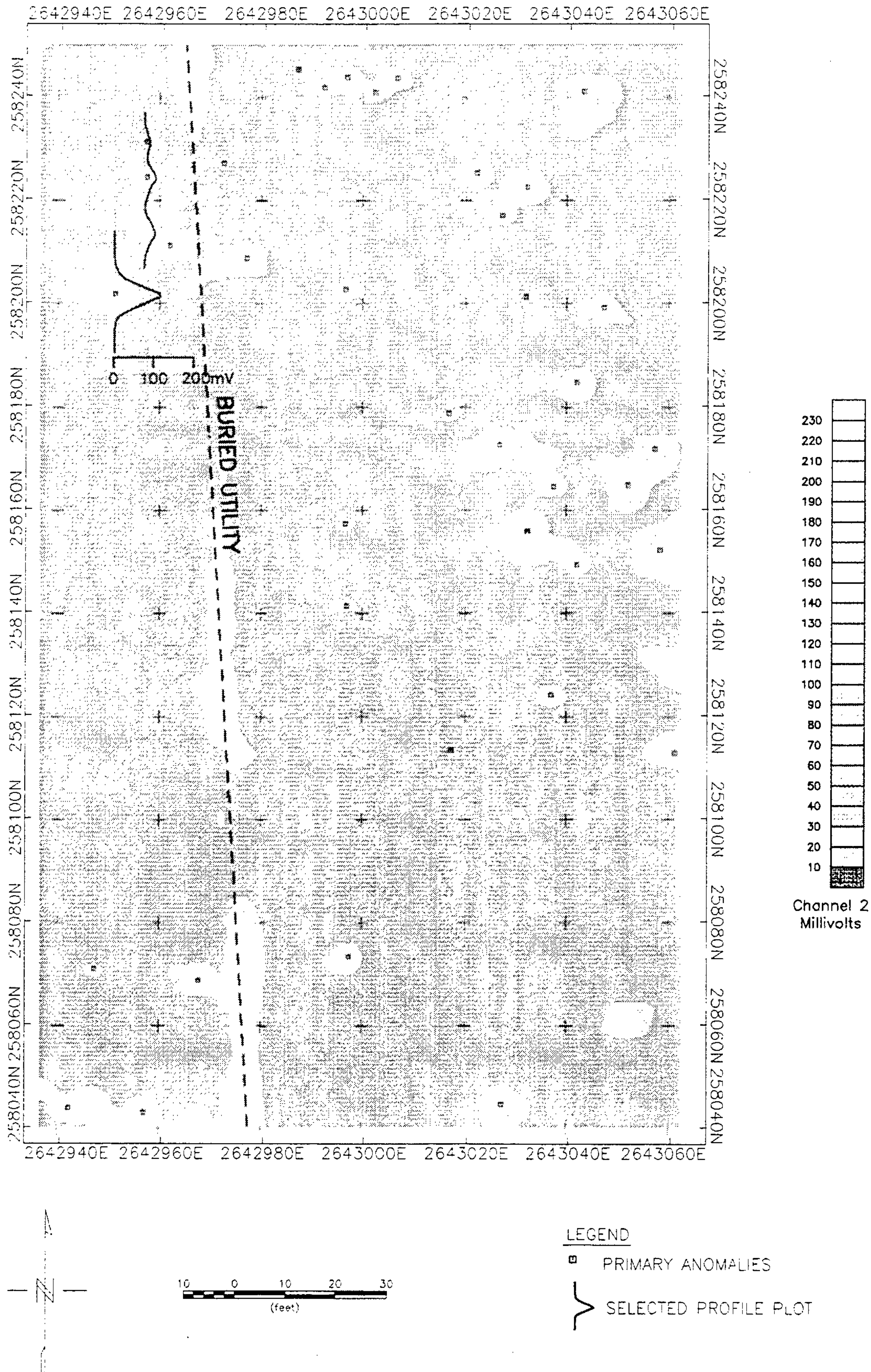

Figure 2.
Contour map of the electromotive force measured with the Geonics EM61 (channel 2) over a section in Fort Monroe, VA.

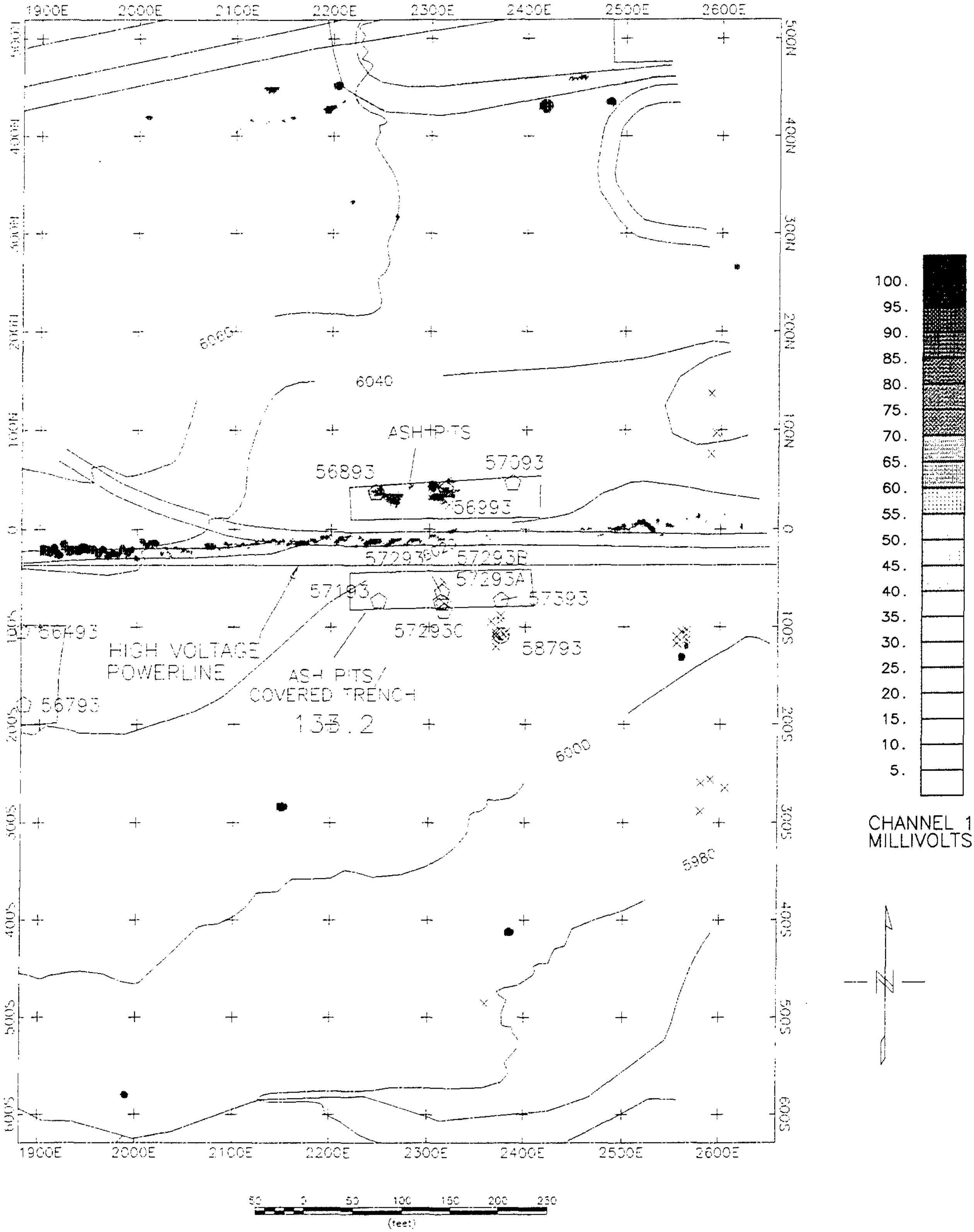

Figure 3A.
Contour map of the electromotive force measured with the Geonics EM61 (channel 2) over ash pits at Rocky Flats, CO. The location of a high voltage power line is superimposed on the map.

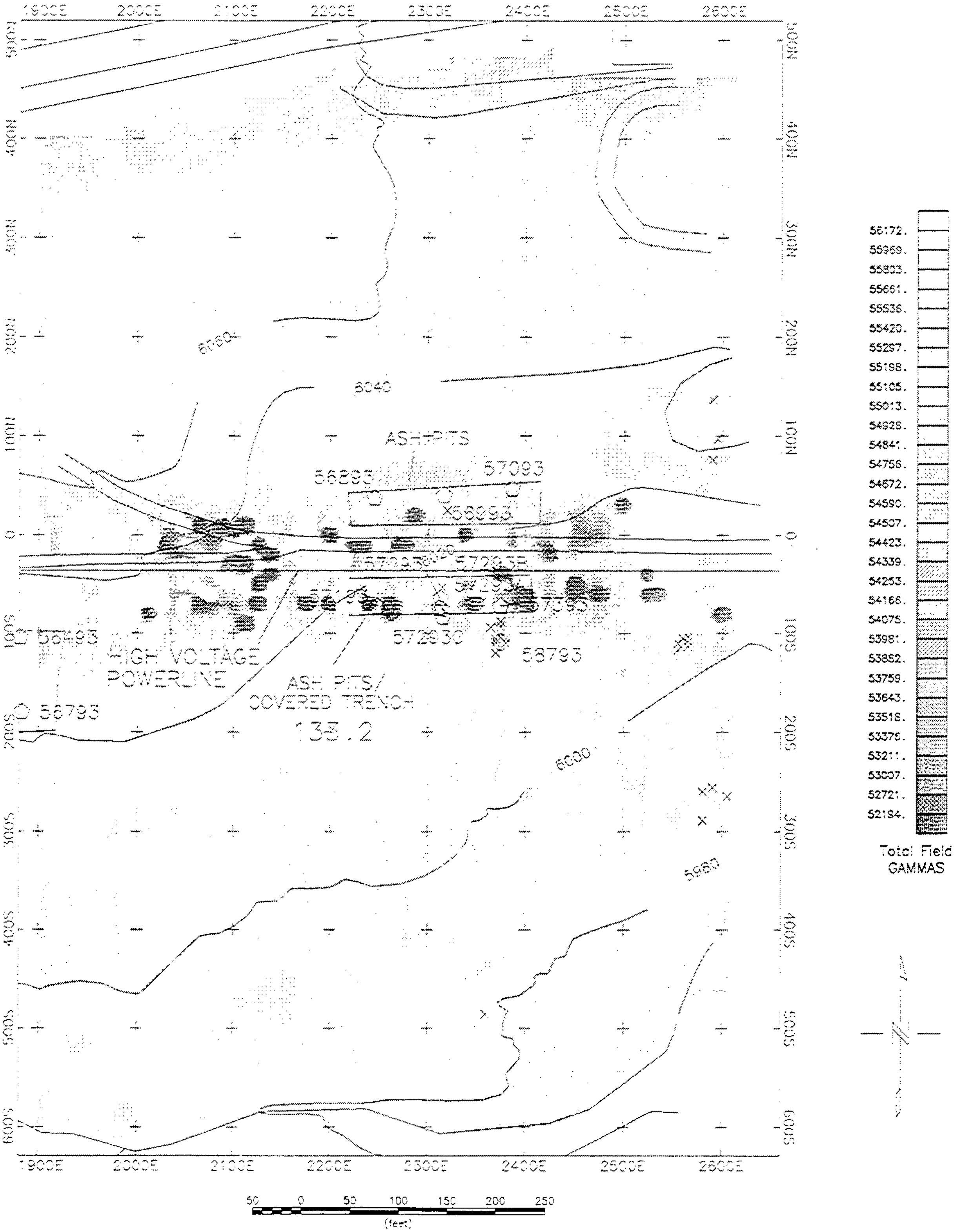

Figure 3B.
Contour map of total magnetic field measurement with Syntrex ENVI-MAG proton precession magnetometer.

SHAPE AND ORIENTATION EFFECTS ON MAGNETIC SIGNATURE PREDICTION FOR UNEXPLODED ORDNANCE

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ABSTRACT

Magnetic detection is a commonly used method for the location and identification of unexploded ordnance (UXO). This technology can be used to construct a magnetic field map of a region suspected to contain UXO. The presence of ordnance results in magnetic anomalies superimposed on the background geomagnetic field. To provide a more realistic estimate of the signature of buried ferrous UXO, this paper presents a model that accounts for the shape, size and orientation of ordnance.

The ordnance shape is approximated by a prolate spheroid, to account for the long aspect ratio typical of ordnance, while preserving an analytic solution. The model considers only the induced magnetization contribution of the total magnetic signature. Employing the prolate spheroidal model, the paper demonstrates that orientation of the prolate spheroid relative to the background geomagnetic field results in magnetic signature values that vary by as much as an order of magnitude. The signature maximum occurs when the semimajor axis of the prolate spheroid is parallel to the geomagnetic field; the signature minimum occurs when the semimajor axis is oriented in the plane orthogonal to the geomagnetic field. In the limit where the observation point is greater then a couple of semimajor axis lengths away from the center of the prolate spheroid, the signature approaches that of a dipole field.

In the case of a prolate spheroidal shell, the magnetic signature is strongly dependent on the outer dimensions, relative permeability and wall thickness of the ferrous ordnance, not the mass. Thus, the magnetic signature should not be scaled with the ferrous mass.

BACKGROUND

The use of magnetic detection techniques to locate buried unexploded ordnance (UXO) has become one of the standard methods used by the UXO community. Techniques for magnetic detection can include the use of full field and vector field magnetic measurements and magnetic field gradient measurements. Detection is complicated by both man-made and naturally occuring magnetic clutter, as well as the time-varying component of the geomagnetic field. In order to maximize detection and assist in the identification of UXO, an understanding of the typical magnetic signatures expected for different types of ferrous ordnance is critical.

The magnetic signature of UXO is related to the physical characteristic of the ferromagnetic materials, typically steel, that are used as the casing for many ordnance items. The magnetic signature of ordnance is usually broken down into two contributions: the remanent magnetization and induced magnetization. The total magnetization, which is a measure of the ordering of the atomic dipole moments of the ferromagnetic material, is related to both the magnetic history of the ordnance item and the magnetic field in which the ordnance item rests. In general, the magnetization can be characterized by the magnetic induction, $\mathbf{B}$, and the geomagnetic field, $\mathbf{H}_g$, where $\mathbf{B}=f(\mathbf{H}_g)$. The functional relationship between the magnetic induction of the ordnance and any applied magnetic field can be drawn in B-H (magnetic induction - magnetic field) space, typically characterized by the hysteresis loop.

Ordnance items are usually subject only to the geomagnetic field or small, man-made magnetic fields. The geomagnetic field is much smaller than the magnetic field required to reach saturation magnetic inductions for ferromagnetic material used in ordnance Therefore to establish theoretical signature estimates of ordnance the paper only looks at the low magnetic field portion of the magnetic induction described by the function $\mathbf{B}=f(\mathbf{H}_{eff})$ during the initial magnetization. Thus, expanding the magnetic induction as a function of the effective internal field results in a linear relationship,

$$\mathbf{B} = \mathbf{B}_r + \mu\mathbf{H}_{eff}, \tag{1}$$

where $\mathbf{B}_r$ is the remanent induction, μ is the magnetic permeability, and $\mathbf{H}_{eff}$ is the effective internal field in the ferromagnetic material. Here only homogeneous, isotropic materials are considered. The remanent induction, sometimes quantified by the remanent magnetization, is defined as the magnetic signature "frozen" into the ordnance item because of previous exposure to magnetic fields. This differs from the often used term remanence, which, in the strict sense, is the remaining field after a ferromagnetic object has reached saturation induction and the magnetic field is then reduced to zero (Jiles, 1991). For most iron-based materials the remanence is much larger than any remanent induction present in ordnance, because the typical fields seen by the ordnance are much smaller than the magnetic field required to reach saturation. Often in the UXO community the remanent induction is referred to as the permanent magnetic field. But, for clarity in discussion of magnetic phenomena, remanent induction and remanent magnetization are used in this paper.

The induced magnetization is a measure of the increase in the magnetization of a ferromagnetic object as an external magnetic field is applied. The induced magentization is related to the second term in equation (1). In an external applied field, the atomic magnetic moments begin to align with the magnetic field inside the ordnance producing the induced magnetization. The alignment mechanism, which is described by the theory of magnetic domains and magnetic domain wall motion, is beyond the scope of this paper. Here the microscopic processes will be approximated by assuming a homogeneous isotropic paramagnetic material. The magnitude of contribution to the magnetic signature by the induced magentization is dependent on the ordnance size, orientation in the geomagnetic field, permeability, and whether it is a hollow shell. Calculation for the overall effect of these parameters is discussed below.

Since most ordnance items are subject only to magnetic fields that are about the size of the geomagnetic field (for this paper, H_g = 0.5 Oe or 50,000 γ), this paper assumes here that the remanent magnetization is small for typical ordnance items. Ordnance items that have seen ground impact will tend to have their magnetic history erased. This loss of magnetic history results because the magnetic domain structure is dependent on the mechanical stress during impact, any acoustic energy imparted to the ordnance item, and heating. For this reason, it is assumed that the magnetization induced by the geomagnetic field is the dominant contributor to the magnetic signature of UXO.

SPHERICAL MODEL

The simplest model used to estimate the size of the magnetic signature induced in a ferrous ordnance item is the spherical model. This model assumes that the ordnance is a solid ferrous sphere with a radius determined by the ferrous mass of the ordnance and the density of steel. This model is attractive because it is easy to use and results in a dipole magnetic signature. However, it has a number of weaknesses:

- the induced signature is incorrectly assumed to be dependent on the ferrous mass;
- the spherical symmetry results in a signature independent of the orientation relative to the geomagnetic field (see Figure 1);
- the sphere does not accurately reflect the demagnetization field within the ordnance item (the demagnetization field is the magnetic field within a finite object caused by the magnetic "poles" at the object's surface).

The first of these items can be accounted for by assuming the sphere is hollow and attempting to determine the field scaled to the volume of the ordnance item. Such a model more accurately reflects the physics of the magnetization process for the ordnance item than does a model that scales the magnetic signature with ferrous mass.

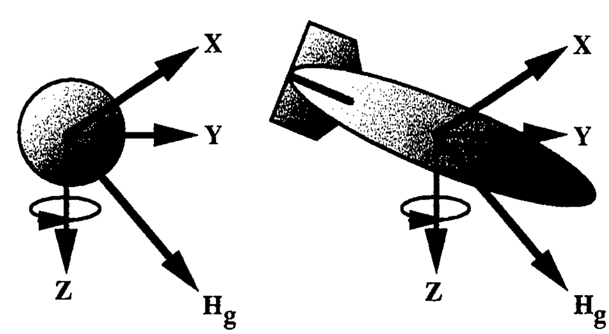

Figure 1. Comparison of the symmetry of a sphere and ordnance. Upon rotation about any axis the sphere appears unchanged to the geomagnetic field. In contrast, the ordnance appearance and magnetostatic interaction changes substantially in different orientations.

Accounting for the issues of orientation within the geomagnetic field and correctly estimating how the demagnetization effects influence the resultant magnetization of the ordnance item is somewhat more complicated. A full model which accounts for the shape,

orientation effects, and the hollow nature of the ordnance is ideal. By approximating the shape of the ordnance item with a cylinder or a prolate spheroid (an ellipsoid with azimuthal symmetry), it is possible to achieve good estimates of the overall effects of these parameters on the magnetic signature of the ordnance item. The prolate spheroid is an attractive geometry when approximating the shape of the ordnance, because the magnetostatic field equation can be solved analytically.

PROLATE SPHEROID MODEL

Modeling the ordnance item as a prolate spheroid can be approached in two different manners. The first is to assume that the magnetic signature is approximated by a dipole field, where the magnetization is calculated for the prolate spheroid geometry (McFee et al., 1990 and Bell et al., 1996). The dipole field approach does not account for any higher moments present in the signature. McFee et al. have shown, however, that the next highest moment is the octapole moment. In most cases, this moment and all higher moments are small compared to the dipole moment's contribution to the magnetic signature. The octapole field drops off as $1/r^5$ compared to the dipole field, which drops off as $1/r^3$.

The second approach is to model the full magnetic field in a prolate spheroidal coordinate system. This approach results in the exact solution to the magnetic field in the presence of a prolate spheroidal ordnance item. This paper presents both these approaches and compares the magnetic signature predicted by the dipole model to the full fild model.

Dipole Field Approach

To determine the magnetic signature assuming only a dipole field, but using the solid ferrous prolate spheroidal geometry, the size and direction of the induced magnetization of the prolate spheroid must be calculated. The induced magnetization calculated here is the volume magnetization. In the case for the solid prolate spheroid, the magnetization is uniform, and thus the total moment of the ordnance is just the volume multiplied by the induced magnetization.

In an applied magnetic field (always the geomagnetic field, $\mathbf{H}_g$, in this paper), the magnetic field inside the prolate spheroid is given by

$$\mathbf{H}_{eff} = \mathbf{H}_g - 4\Pi\,\mathbf{N}\cdot\mathbf{M}, \qquad (2)$$

where $\mathbf{H}_{eff}$ is the effective field within the spheroid, $\mathbf{N}$ is the demagnetization factor, and $\mathbf{M}$ is the magnetization (Chikazumi, 1986). The demagnetization factor is a tensor. For the prolate spheroid, the tensor can be diagonalized by rotation into a reference frame defined by the principal axes of the spheroid. Thus, it can be treated as a vector quantity. The components of the demagnetizaiton field for a prolate spheroid are given by

$$N_l = \frac{1}{4\Pi(k^2-1)}\left(\frac{k}{\sqrt{(k^2-1)}}\ln\left(k+\sqrt{k^2-1}\right)-1\right), \qquad (3a)$$

and

$$N_d = \frac{(1-4\Pi N_l)}{8\Pi}, \qquad (3b)$$

where the subscripts l and d represent the length or semimajor axis and diameter or semiminor axis demagnetization factors, respectively, and k is the ratio of the semimajor axis to semiminor axis (Chikazumi, 1986). The azimuthal symmetry of the prolate spheroid results in a single value for the demagnetization factor in the plane orthogonal to the semimajor axis.

In a homogeneous isotropic magnetic material the induced magnetization is related to the effective field by, $\mathbf{H}_{eff} = \mathbf{M}\,/\,(\mu-1)$. The magnetization can be written in terms of the geomagnetic field, which has its three components expressed relative to the principal axes of the spheroid by

$$M_i = \frac{(\mu-1)\,H_{gi}}{1+4\Pi(\mu-1)N_i}, \qquad (4)$$

where each i-th component is along one of the three principal axes. Table 1 gives values for the magnetization parallel to the length and diameter for six different prolate spheroids, including a sphere, assuming a relative permeability of $\mu = 1000$. Note that relative to the magnetization of a sphere, the magnetization for a prolate spheroid with a length to width ratio of six increases by a factor of 7.6 when magnetized parallel to the long axis, and decreases by a factor of 1.4 relative to the sphere when magnetized perpendicular to the long axis. The semimajor axis is an easy direction of magnetization. The semiminor axis is a hard direction of magnetization. Since the magnetic signature is proportional to the magnetization, the prolate spheroid will exhibit a much larger magnetic signature if its long axis is oriented parallel to the geomagnetic field than it will if its long axis is perpendicular to the geomagnetic field.

Figure 2 shows the magnetization in both the easy and hard directions for multiple relative permeabilities normalized to the magnetization of a sphere. The higher the permeability, the larger the difference between magnetization in the prolate spheroid and magnetization of the sphere. For large relative permeability, magnetization relative to that of the sphere asymptotically approaches 3(μ-1) in the hard direction, and 2/3 in the easy direction as the length to width ratio increases The magnetic signature estimated by a spherical model does not correctly estimate the overall magnitude of the magnetization or the magnetic signature (McFee et al., 1990; Bell et al., 1996).

Table 1. Magnetization for Various Prolate Spheroids[a]

Length to Diameter	Magnetization[b] along Length	Magnetization along Diameter
1	3.0	3.0
2	5.7	2.4
3	9.1	2.2
4	13.1	2.2
5	17.6	2.1
6	22.6	2.1

[a] Magnetization in both the semimajor and semiminor axes is calculated using equation (4).
[b] Magnetization is in arbitrary units assuming a relative permeability, μ = 1000.

Since the magnetization is a vector quantity, the relative size and direction of the magnetization can be influenced by the orientation of the prolate spheroid in the geomagnetic field. This effect can be demonstrated by determining the magnitude and direction of magnetization as the ordnance item is rotated in a plane intersecting the long axis of the ordnance item (see Figures 3 and 4). As the ordnance item is rotated the direction of magnetization follows, but lags the semimajor axis. When the prolate spheroidal ordnance is at an angle defined by

$$\theta_m = \tan^{-1}\left(\frac{1+4\,\Pi(1-\mu)\,N_d}{1+4\,\Pi(1-\mu)\,N_l}\right)^{1/2}, \qquad (5)$$

with respect to the applied magnetic field, the magnetization begins to move back towards the direction of the geomagnetic field, and is again parallel to that field when the ordnance item has rotated 90 degrees. Figure 3 shows the angular separation between the direction of magnetization and the semimajor axis of the ordnance item as the ordnance is rotated from parallel to perpendicular with respect to the geomagnetic field. Figure 4 shows the magnitude of the magnetization for three prolate spheroids. The shape can affect the ease of magnetization along each of the principal axes. The magnitude of the magnetization in each of these direction is highly dependent on the shape and orientation relative to the geomagnetic field. This dependence results in an induced magnetization vector that can be out of alignment with the long axis of the ordnance item and with the geomagnetic field. Thus, for certain orientations, the resulting dipole magnetic signature will not line up with either the geomagnetic field or the long axis of the prolate spheroids.

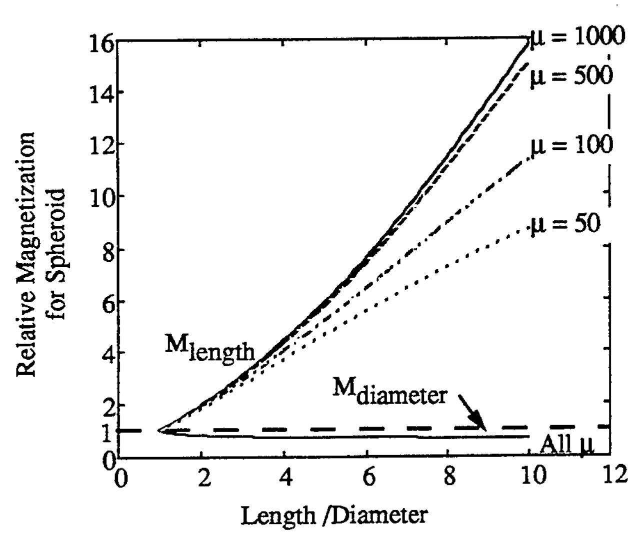

Figure 2. The relative magnetization of a prolate spheroid, normalized to the magnetization of a sphere, is shown for four values of the relative permeability. Magnetization along the long axis and the diameter are shown.

The magnetic signature can be found by using the magnetization vector given in equation (4), which results in a magnetic signature given by

$$\mathbf{H}_{sig} = -V\,\frac{\mathbf{M}}{\mathbf{R}^3} + 3\,V\,\frac{\mathbf{R}\,(\mathbf{R}\cdot\mathbf{M})}{\mathbf{R}^5}\,, \qquad (6)$$

where $\mathbf{H}_{sig}$ is the magnetic signature of the prolate spheroid, **R** is the vector distance from the spheroid to the observation point, and V is the volume of the spheroid (Jackson, 1975). To find $\mathbf{H}_{sig}$ in the earth frame of reference, $\mathbf{H}_{sig}$ must be rotated into the earth frame (see Figure 5).

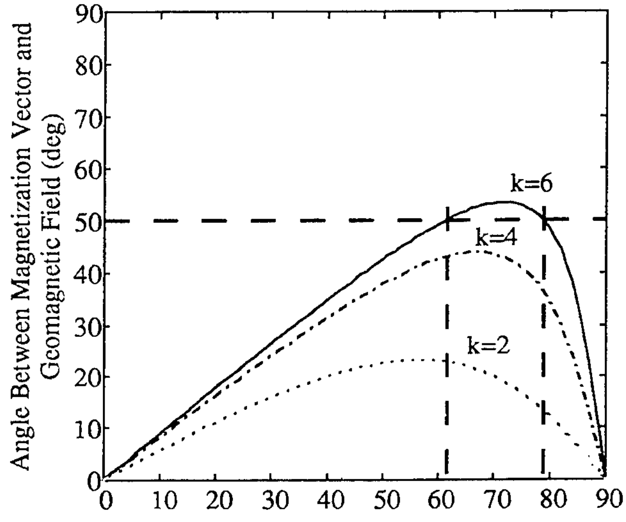

Figure 3. The direction of the magnetization vector relative to the geomagnetic field as a prolate spheroid is rotated. The semimajor axis moves from parallel to perpendicular to the geomagnetic field. k is the ratio of the length to the diameter. Relative permeability is much greater than one. For example, for a prolate spheroid, with k = 6, the magnetization vector is at an angle of 50° relative to the geomagnetic field when the semimajor axis of the prolate spheroid points either approximately 62° or 78°.

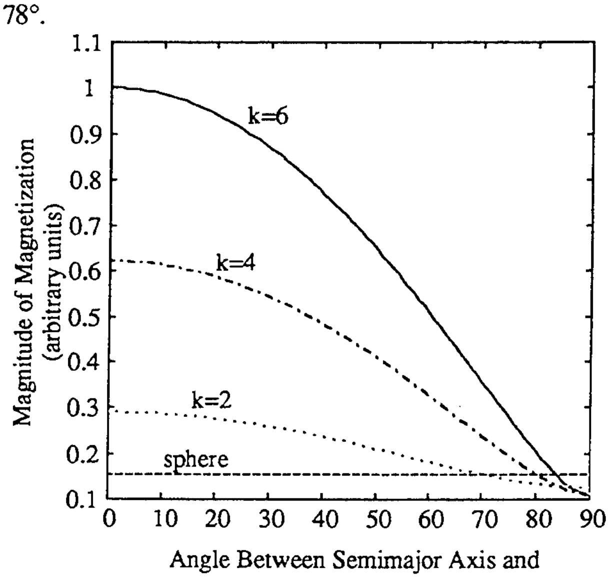

Figure 4. The magnitude of magnetization as a prolate spheroid is rotated. Here, the semimajor axis moves from parallel to perpendicular to the geomagnetic field. k is the ratio of the length to the diameter. Relative permeability is much greater than one.

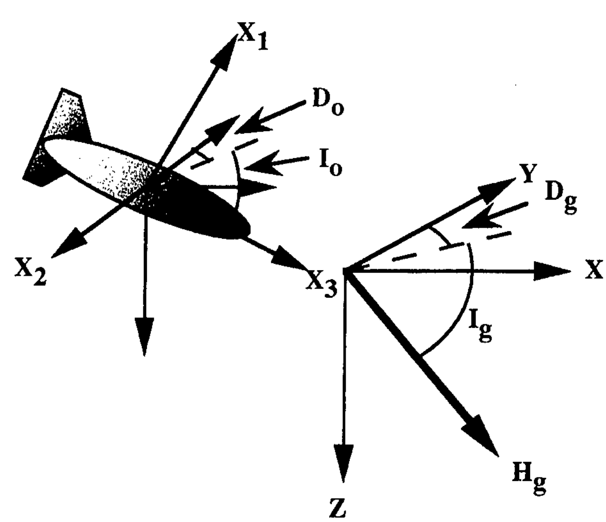

Figure 5. The earth frame coordinate system used in this paper. The positive z-axis points toward the center of the earth. Here, I_g and D_g are inclination and declination of the geomagnetic field, respectively, relative to the earth frame of reference. I_o and D_o are the inclination and declination of the ordnance, respectively, relative to the earth frame of reference.

Full Field Approach

Modeling ordnance using the full field approach requires the solution to the magnetostatic field equation in prolate spheroidal coordinates. In this coordinate system Laplace's equation, $\nabla^2\Phi(\eta, \xi, \phi) = 0$, has an analytic solution, where Φ is the magnetic scalar potential both inside and outside the ordnance item and (η, ξ, ϕ) are the three orthogonal coordinates. The principal axes of the prolate spheroid can be expressed as follows:

$$\left(x_1^2 + x_2^2\right)^{1/2} = c_1\left[\left(1-\xi^2\right)\left(\eta^2-1\right)\right]^{1/2},$$

$$x_3 = c_1\,\xi\,\eta, \tag{7}$$

$$\frac{x_2}{x_1} = \sin\phi,$$

where c_1 is $(c^2-b^2)^{1/2}$ and c and b are the semimajor and semiminor axes, respectively. Here η is the analog to r in the spherical coordinate system, ξ is the analog to θ, and ϕ is the azimuthal coordinate (Smythe, 1989).

To determine the full solution for a general uniform magnetic field, the potential can be broken down into two cases: (1) the component of the geomagnetic field parallel to the semimajor axis of the prolate spheroid, and (2) two orthogonal components of the geomagnetic field along the remaining two principal axes of the prolate spheroid. Once these are solved, the full solution is the superposition of the three potentials. The first scalar potential is

$$\Phi_1 = -H_{g1}\, c_1\, \eta\, \xi + B_1\, \xi\, Q_1(\eta), \qquad (8)$$

where H_{g1} is the component of the geomagnetic field along the semimajor axis, B_1 is a constant obtained by matching the magnetostatic boundary conditions, and Q_1 is a prolate spheroidal harmonic. The second set of magnetic scalar potential are:

$$\Phi_{di} = -H_{gdi}\, c_1 P_1^1(\eta) P_1^1(\xi) + B_d P_1^1(\xi) Q_1^1(\eta) \begin{bmatrix} \sin\phi \\ \cos\phi \end{bmatrix}, \quad (9)$$

where P_1^1 and Q_1^1 are prolate spheroidal harmonics, B_d is a constant obtained by matching the magnetostatic boundary conditions, and the i-components are the two principal axes orthogonal to the semimajor axis.

The resultant magnetic field external to the prolate spheroid is $\mathbf{H}_t = -\nabla\Phi(\eta, \xi, \phi)$. This field is then transformed back into cartesian coordinates and rotated into the earth frame of reference. $\mathbf{H}_t$ is the full field solution, meaning that it is the superposition of the geomagnetic field and the signature from the prolate spheroid.

The full magnetic field signature of the prolate spheroidal ordnance item is the vector difference between total external magnetic field and the geomagnetic field, $\mathbf{H}_{sig} = \mathbf{H}_t - \mathbf{H}_g$. In the case of a vector magnetometer, $\mathbf{H}_{sig}$ is determined directly by correcting for the geomagnetic field. For the total field magnetometers, i.e., Cs vapor or proton precession, the magnetic signature is determined by subtracting the magnitude of the total field from the magnitude of the geomagnetic field:

$$|\mathbf{H}_m| = (\mathbf{H}_{sig} + \mathbf{H}_g)^{1/2} - |\mathbf{H}_g|, \qquad (10)$$

where $|\mathbf{H}_m|$ is the measured magnetic signature of the ordnance item. The resulting measured magnetic field is, to first order, the projection of the magnetic field caused by magnetization of the ordnance in the direction of the geomagnetic fields (McFee, 1990). Because of the difference between the signature measured with a vector magnetometer and a total field magnetometer, care must be taken when comparing the two. This paper considers the magnetic signature to be only the induced magnetization as presented in equation (10), i.e., the magnetic signatuer measured by a total field magnetometer.

Figures 6 through 8 show the magnetic signature of ordnance modeled as prolate spheroids using the full field model. The magnetic field map is for a measurement plane 150 cm above the center of volume. For these calculations the geomagnetic field is 50,000 γ, with 65° inclination and 0° declination. For all three examples the inclination is 0°. The declinations are 0°, 45° or 90°. The maximum of the signature decreases as the inclination increases. In addition, the orientation of the signature minimum-to-maximum does not line up with either the semimajor axis or the geomagnetic field when the ordnance has a declination between 0° and 90° (see Figure 7). This is consistent with the results presented earlier for the dipole field model.

Comparison of Full Field and Dipole Field Signatures

Having solved the boundary value problem for the solid prolate spheroid, it is now possible to compare the magnetic signature of ordnance modeled with the dipole field approach and the full field approach. At this point, it is interesting to look at the error resulting from ignoring the higher order terms when using the dipole field approach. To do this, the magnetic signature of an ordnance size prolate spheroid is investigated at different distances above the center of volume. Table 2 lists the differences in the peak signature for a model of a 155 mm projectile, oriented vertically relative to the ground (inclination 90°), at different distances from the total field magnetometer. Table 3 lists the differences in the peak signature for a model of a 155mm projectile, oriented horizontally in an east-west configuration (inclination 0°, declination 90°) relative to the ground, at different distances from the total field magnetometer.

The error in the dipole model, relative to the full model, is large when the measurement plane is close to the ordnance. For these calculations, the length of the ordnance is assumed to be 31 cm. Thus for the vertical orientation, at a distance of 50 cm, the measurement plane is only 19 cm from the top of the ordnance. For the ordnance that has an inclination of 0°, the measurement plane is only 42 cm from the ordnance. For measurement distances greater than a couple of semimajor axes from the center of volume of the ordnance, the dipole model is generally within 10 percent of the full field model.

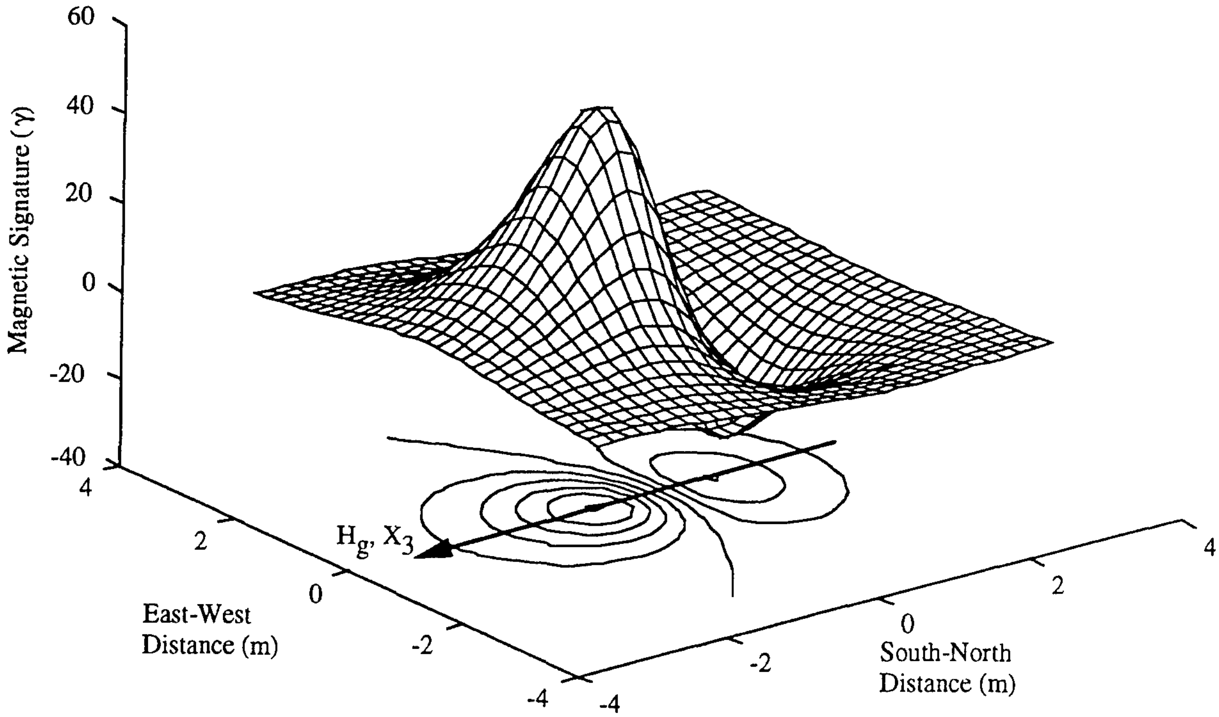

Figure 6. The magnetic signature of a prolate spheroid model of a 155 mm projectile. The projectile has inclination and declination of 0° and has its center of volume 150 cm from the measurement plane. The geomagnetic field has inclination of 65° and declination of 0°. The relative permeability of this spheroid is 100. X_3 is the semimajor axis of the spheroid. H_g is the projection of the geomagnetic field on the measurement plane.

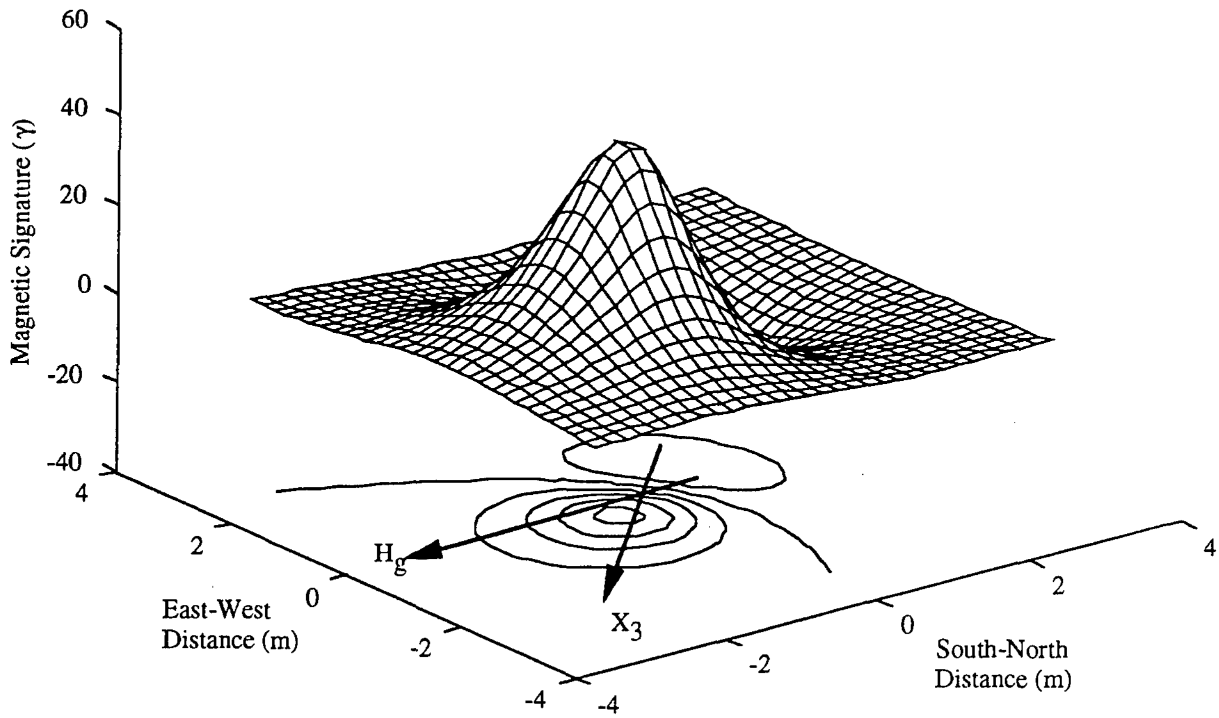

Figure 7. The magnetic signature of a prolate spheroid model of a 155 mm projectile. The projectile has inclination 0° and declination of 45° and has its center of volume 150 cm from the measurement plane. The geomagnetic field has inclination of 65° and declination of 0°. The relative permeability of this spheroid is 100. X_3 is the semimajor axis of the spheroid. H_g is the projection of the geomagnetic field on the measurement plane.

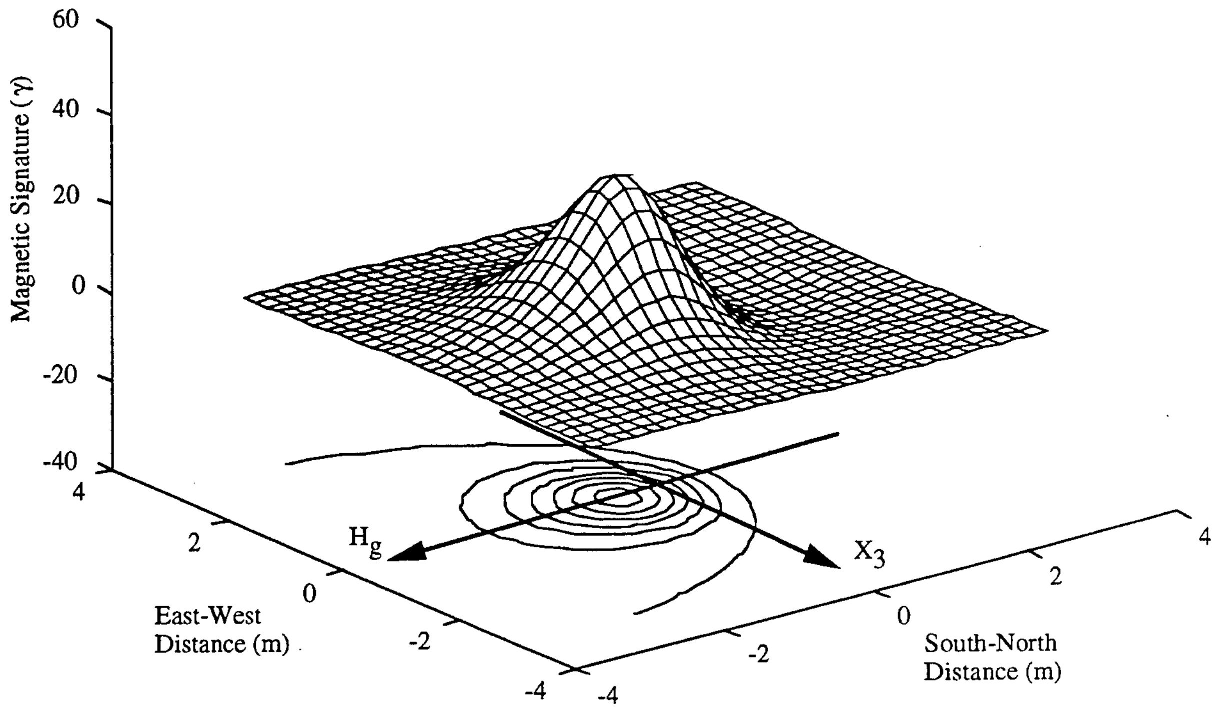

Figure 8. The magnetic signature of a prolate spheroid model of a 155 mm projectile. The projectile has inclination 0° and declination of 90° and has its center of volume 150 cm from the measurement plane. The geomagnetic field has inclination of 65° and declination of 0°. The relative permeability of this spheroid is 100. X_3 is the semimajor axis of the spheroid. H_g is the projection of the geomagnetic field on the measurement plane.

SOLID VERSUS SHELL

So far the ordnance has been approximated by a solid spheroid. In reality, ordnance is not made of solid ferromagnetic material. Therefore it is better modeled as a shell. To quantify the overall effect on the magnetic signature of a shell relative to a solid object this paper investigates the spherical shell and the prolate spheroidal shell.

Spherical Shell

The magnetic signature caused by a spherical shell can be calculated by solving the Laplace equation, $\nabla^2\Phi(r, \theta, \phi)= 0$, matching the boundary conditions at both the inner and outer surfaces of the sphere. The relative magnetization of the shell to the sphere can be shown to be

$$\frac{M_{shell}}{M_{solid}} = \left[\frac{(2\mu+1)(\mu+2)}{(2\mu+1)(\mu+2)-2(\mu-1)^2\frac{a^3}{b^3}}\right]\left(1-\frac{a^3}{b^3}\right), \quad (11)$$

where b is the outer radius and a is the inner radius of the sphere (Jackson 1975). Figure 9 shows the relative magnetization for five different relative permeabilities. For large relative permeability the shell has virtually the same net magnetization as the solid sphere. Only for very thin shells and for low relative permeability does the spherical shell exhibit a decrease in the magnetization resulting in a decrease in the magnetic signature. For example, for a relative permeability of 100 and a shell thickness of five percent of the radius, the magnetization is 80 percent of the magnetization for the solid sphere.

Prolate Spheroidal Shell

A similar calculation can be done for the prolate spheroidal model of ordnance. To assure that the Laplace equation has an analytic solution, the minner and outer surfaces are confocal prolate spheroids. In this case, a wall thickness is larger along the semiminor axis than along the semimajor axis. This condition is required by the geometry of the confocal spheroids. This type of shell does not accurately represent an actual ordnance item, however, it will give a lower bound for the effects of hollow ferrous ordnance.

Table 2 Comparison of Peak Magnetic Signature at Different Distances for Vertical Orientation[a]

Distance to sensor (cm)[b]	Peak Full Signature (γ)	Peak Dipole Signature (γ)[c]	Maximum Signature Delta (%)[d]
50	7190	4550	38.8
100	638	574	10.3
150	178	170	4.5
200	73.7	71.9	2.5
250	37.4	36.8	1.6

[a] Signatures are calculated assuming the geomagnetic field is 50,000 γ, with 65° inclination and 0° declination. Length is 62 cm, diameter is 15.5 cm .

[b] The distance to the sensor is measured from the center of volume of the prolate spheroid vertically to the plane of measurement.

[c] Signature calculated using equation (10) and equation (6).

[d] Maximum delta is the largest absolute difference between the full and dipole model normalized to the full field signature at that point.

Figure 10 shows the peak magnetic signature for a prolate spheroidal shell relative to the solid prolate spheroid as a fuction of shell thickness measured along the semimajor axis. The five different curves represent relative permeabilities ranging from 50 to 1000. As is the case with the spherical shell, the magnetic signature does not differ substantially as the shell thickness decreases, until the thickness is small. For very large relative permeabilities, only very thin shells deviate substantially from the solid magnetic signature. Still, the decrease is geater in the prolate spheroidal case than that of the sphere. This difference is strongly related to the non-uniform shell thickness required to achieve the analytic solution to the magnetic field equations. Since, in real ordnance the wall thickness does not narrow to such an extent as required in the analytic model, the relative magnetization will be larger than that shown in Figure 10. It can be concluded from both the spherical shell and prolate spheroidal shell models that the outer ferrous volume of the ordnance is critical to the magnitude of the magnetic signature. The ferrous mass does not influence the induced signature of ordnance.

Table 3 Comparison of Peak Magnetic Signature at Different Distance for Horizontal Orientation[a]

Distance to sensor (cm)[b]	Peak Full Signature (γ)	Peak Dipole Signature (γ)[c]	Maximum Signature Delta (%)[d]
50	744	882	-18.7
100	105	110	-4.8
150	32.0	32.7	-2.2
200	13.6	13.8	-1.3
250	7.0	7.1	-0.8

[a] Signatures are calculated assuming the geomagnetic field is 50,000 γ, with 65° inclination and 0° declination. Prolate spheroid is oriented with 0° inclination and 90° declination. Length is 62 cm, diameter is 15.5 cm .

[b] The distance to the sensor is measured from the center of volume of the prolate spheroid vertically to the plane of measurement.

[c] Signature calculated using equation (10) and equation (6).

[d] Maximum delta is the largest absolute difference between the full and dipole model normalized to the full field signature at that point.

SUMMARY

This paper presents two models that approximate the shape of ordnance as a prolate spheroid. Such an approximation permits realistic determination of orientation effects relative to the geomagnetic field. Both a dipole and full field model are discussed. In both cases, there are substantial orientation effects on the magnetic signature of elongated ordnance. Deviation from the full field model magnetic signature by the dipole model is small if the measurement plane is greater than a few semimajor axes away from the center of volume. Thus, the dipole field approximation for ordnance is valid as long as both the magnitude and direction of the magnetization are accurately determined.

The magnetic signature is independent of the ferrous mass. Instead, the critical parameters for magnetic signature are outer volume, shell thickness, relative permeability, ratio of length to diameter, and orientation in the geomagnetic field.

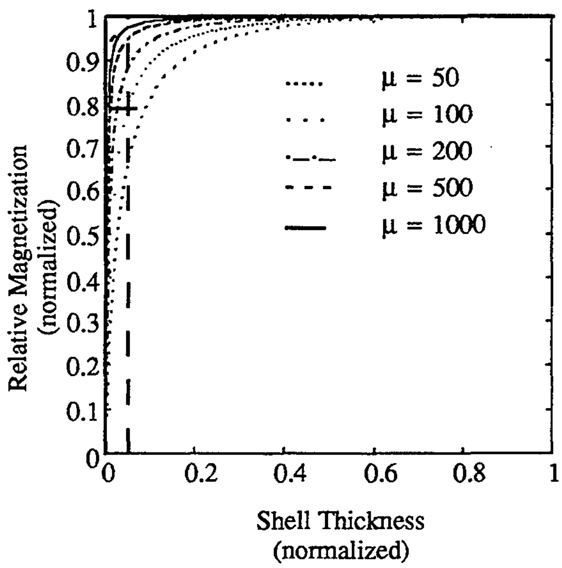

Figure 9. The magnetization as a function of shell thickness is shown for different relative permeabilities. Shell thickness of one represents a solid sphere. The relative magnetization of a sphere is normalized equal to one. For a spherical shell, with thickness of five percent of the total radius and relative permeability of 100, the magnetization is approximately 80 percent that of the solid sphere.

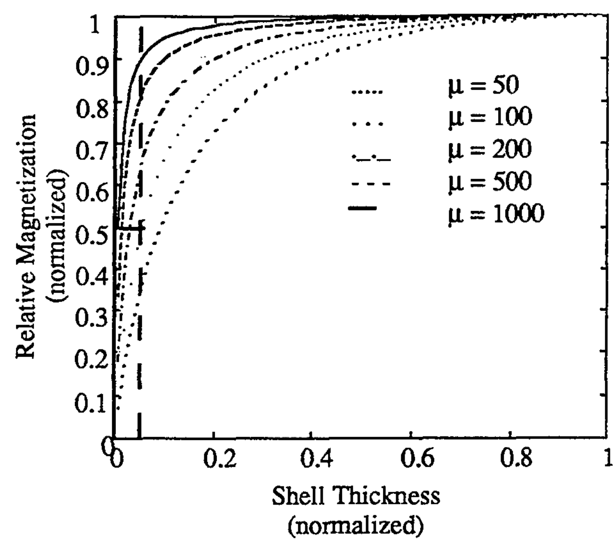

Figure 10. The magnetization of a prolate spheroid as a function of shell thickness is shown for different relative permeabilities. The spheroid is magnetized along the semimajor axis. Shell thickness of one represents a solid spheroid. Relative magnetization of one indicates a solid spheroid. For a spheroidal shell, with wall thickness of five percent along the semiminor axis and relative permeability of 100, the magnetization is approximately 50 percent that of the solid spheroid.

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A COMPARISON OF MAGNETIC SURVEY METHODS

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INTRODUCTION

Passive magnetic sensors, including total field sensors, field component sensors, and gradiometers are currently the preferred instruments for detecting UXO. Field surveys with these instruments invariably find large amounts of ferrous material (in any areas that have been used by man). Typical surveys will also find some UXO, if present. But will the survey find all the UXO, or most of it, or only a small fraction of it? To answer this question, it is necessary to quantify the detection performance of the survey. This paper presents a method for modeling detection performance of surveys with passive magnetic sensors, and demonstrates the method with data from three field surveys. In a survey planning phase the described methodology can be used to compare proposed sensors and survey methods. After a survey it can be used to demonstrate quantitatively that the requirements of the survey have been met.

The performance model comprises separate models for the magnetic signal from UXO, the measurement noise, the survey measurement process, and the process for declaring detections (figure 1). The magnetic signal is modeled as a dipole moment induced in the ferrous casing of the UXO. This signal depends most strongly on the object depth and size. The measurement noise for 'total field' surveys is dominated by spatially correlated noise with increasing amplitude at longer spatial scales. This noise is virtually eliminated in gradiometer surveys where the dominant noise source is that induced by relative motion between the two sensors. Modeling the measurement process is important for objects whose surface footprint is small compared to the area covered by a typical measurement. The process of declaring detections generally depends on the noise encountered in the survey. This is difficult to estimate before the data are collected if environmental noise exceeds system noise. The output of the model is the probability of detection as a function of UXO depth and size.

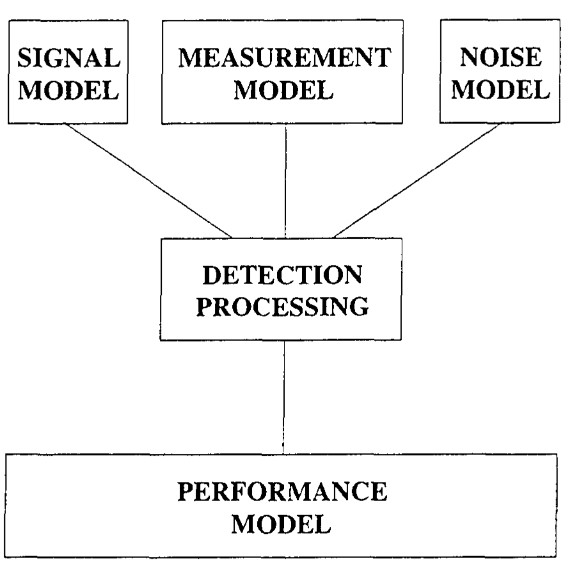

Figure 1. Schematic diagram of performance model components.

We will first describe the parts that go into the performance model and then demonstrate the technique with data from several field surveys. In cases where the ground truth is known, the model estimates agree well with the observed performance. The model is then used to compare current survey performance with that required for detecting UXO.

THE MAGNETIC SIGNATURE OF UXO

The outer casing of most UXO is made of ferrous material which produces the observed magnetic signal. Any ferrous material will become magnetized when placed in a magnetic field (such as that of the Earth). This induced magnetization distorts the field lines in the vicinity of the object, and it is this distortion which is measured in magnetic surveys. Outside of the object the magnetic field distortion satisfies Laplace's equation and may be described by an expansion of spherical harmonics. For compact objects like UXO, at typical detection distances, the first term in the expansion, the dipole term, is sufficient to describe the field distortion. The dipole field depends only on the location of the body, the size of the magnetic moment, and the angles between the magnetic moment and the Earth's field.

The magnetic field for a dipole with magnetic moment $\vec{m}$, at position $\vec{r}$, measured from the center of the dipole, in MKS units is:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \frac{3\hat{r}\,(\hat{r}\cdot\hat{m}) - \hat{m}}{|\vec{r}|^3} |\vec{m}| , \qquad (1)$$

where μ_0 is the vacuum permeability. To estimate the magnetic moment we first assume that the magnetization has the same amplitude as if it were wholly induced. The validity of this assumption has been borne out in our experience with magnetic measurements of UXO and clutter objects (Bell, 1994). For illustration we will first consider the object to be a sphere. The induced moment for a sphere of radius a takes the simple form:

$$\vec{m} = \frac{4\pi}{\mu_0} a^3 \left(\frac{\mu - 1}{\mu + 2}\right) \vec{B}_E , \qquad (2)$$

where $\vec{B}_E$ is the local Earth field and μ is the magnetic permeability of the casing. This result may be combined with equation (1) to yield:

$$\vec{B}(\vec{r}) = \frac{a^3}{|r|^3} \left(3\hat{r}\,(\hat{r}\cdot\hat{B}_E) - \hat{B}_E\right)\left(\frac{\mu - 1}{\mu + 2}\right) |\vec{B}_E| . \qquad (3)$$

Although most UXO is not spherical some features of this result hold for realistically shaped objects. Note that the first term in parentheses determines the direction of $\vec{B}(\vec{r})$ but does not have a large effect on the amplitude. In fact over all relative angles of $\vec{B}_E$ and $\hat{r}$ this factor varies only from 1 to 2. The ferrous material in UXO is typically of large ($\mu > 100$) permeability, so the second parenthetical expression in the above equation is nearly 1, and has very small variability. The dependence of the dipole field on both object size and distance (i.e., depth) is cubic.

Note that the solution in equation (3) depends only on the size of the induced object, not its mass. This is because ferrous objects tend to exclude magnetic field lines from their interior. For typical ferrous UXO ($\mu > 100$) the magnetic field lines are restricted to the outer few percent of the object. Thus, the thickness of the ferrous casing does not affect the magnetic signal as long as it is greater than a few percent.

Total field sensors measure the amplitude of the vector sum of $\vec{B}$ and $\vec{B}_E$. Of these $\vec{B}_E$ is much larger, so the measured amplitude is essentially equal to the $\vec{B}_E$ plus the component of $\vec{B}$ in the direction of $\vec{B}_E$ (the average Earth field is usually subtracted from this result). Gradient sensors measure the difference in total field (or components) at two locations. Differencing the two measurements eliminates the average Earth field automatically and changes the dependence on distance to r^{-4}.

Real UXO is not spherical; a prolate spheroid is a closer approximation to typical UXO shapes. The solution for the magnetic field distortion induced by a prolate spheroid in a uniform magnetic field is described in many electrodynamics texts (see for instance, Stratton, 1941). For this problem the equations describing the field distortion are more complicated than those given above for the sphere and will not be repeated here. External to the object the solutions may still be expanded in spherical harmonics with a leading dipole term. Very close to the object, higher order terms in the multipole expansion may be appreciable. These will not affect our performance calculations since the probability of detection of UXO at such close range is nearly 1 anyway. At typical detection ranges the field distortion remains that of a dipole source (Altshuler, 1996). For a prolate object the amplitude and direction of the induced dipole moment depend on additional parameters: the aspect ratio of the object and its orientation relative to the Earth's field. The dominant dependencies on object size (a^3) and distance (r^{-3} for total field and r^{-4} for gradiometer) remain. Since these factors are dominant, we will examine the measured signal as a function of object size and depth (averaging over the other parameters increases the variance of resulting detection probabilities, as will be discussed below).

SIGNAL AMPLITUDE VERSUS SIZE AND DEPTH

As noted above, the amplitude of the total field magnetic signal from buried UXO is proportional to the cube of the object radius and inversely proportional to the cube of the distance from object center to the sensor. The strong dependence on these two parameters defines the limits of magnetic survey techniques for finding buried UXO, as illustrated in figure 2.

In figure 2 the peak signal amplitude at the ground surface for an induced spherical target is plotted on the vertical axis versus object size and depth (this is the sharply dipping surface). The projection of this surface is shown as a two-dimensional image in the size/depth plane. The shading of the image is scaled to show how the steepness of the amplitude surface affects detection probability. The object size is specified as shell diameter in mm. When using the sphere model the diameter is calculated from the shell (with typical aspect ratio) with volume equal to that of the sphere. Note that the vertical axis is logarithmic and that over the range of sizes and depths shown (which are typical for UXO) the signal amplitude varies by almost 8 orders of magnitude.

The dashed line plotted on the projection to the size-distance

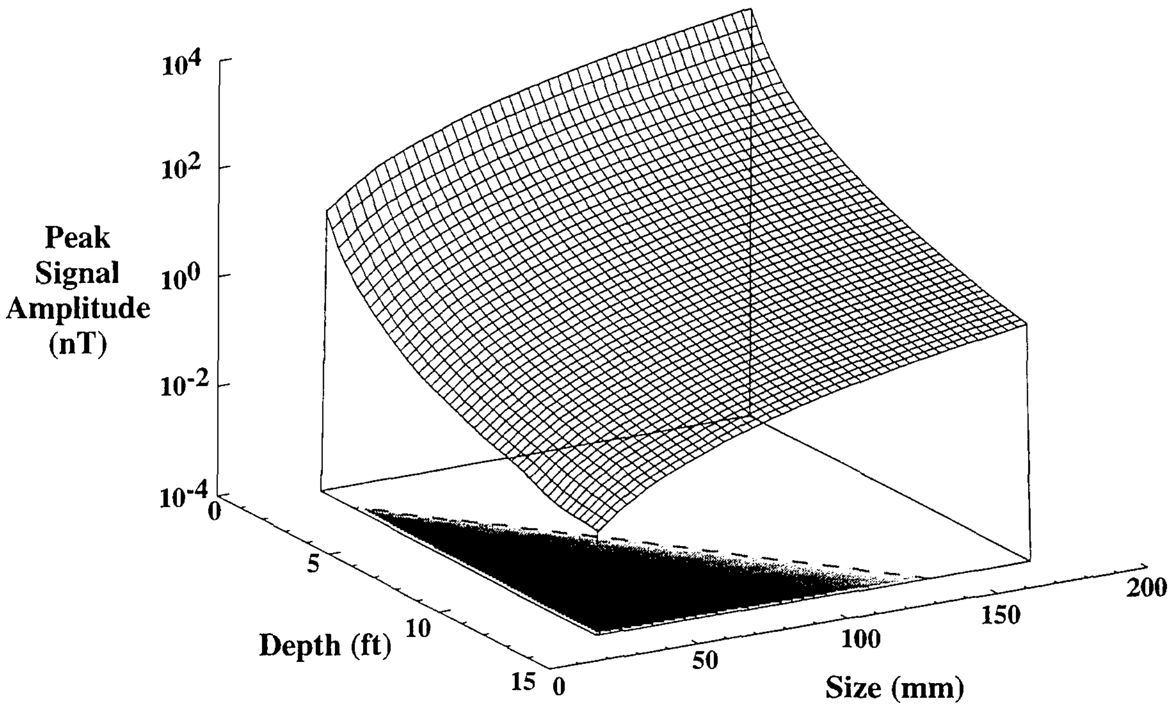

Figure 2. Peak signal amplitude versus size and depth. Shading on horizontal surface represents detection probability. Dashed line is contour at signal level of 1 nT.

plane is the 1 nT (1 gamma) signal level; a typical noise level for magnetometer systems. The shading of the surface is meant to indicate in a schematic way the effect this steep surface has on UXO detection. If the actual threshold level of a survey is near 1 nT (the threshold will be about 3 times the noise level for unprocessed threshold detection) then objects in the white region of the surface have signals so large that they will **always** be detected. Objects in the black region have signals so small that they are **never** detected, regardless of operator experience or detection method used. Objects in the grey region may or may not be detected depending on the other parameters not shown (orientation, aspect ratio, etc.), and on the details of the survey. We will refer to the grey region as defining the "critical surface" between assured detection and prohibited detection. The key point is that because of the steepness of the amplitude surface the width of the critical surface is very narrow. We will show the output of the performance model as two-dimensional images in size/depth space with the shading reflecting quantitatively the estimated detection probability. When looking at these figures recall that the sharply dipping three-dimensional amplitude surface of figure 2 is what drives the detection probabilities. (In this paper, due to restrictions on color figures, we use black to represent low detection probability, white for high detection probability and grey for the critical surface region. We prefer a "stoplight" palette with red for low probability, green for high, and a yellow critical surface, as will be used in the slides accompanying the oral presentation.)

PERFORMANCE MODEL

Figure 2 shows in a qualitative way that the detection probability for a magnetic survey is near 1 for large shallow UXO and near 0 for small deep objects, with a narrow critical surface in between. To quantify detection performance it is necessary to augment the signal amplitude information described in the preceding sections with models for the measurement noise, measurement locations and detection processing. These will be considered in turn.

For total field surveys most of the noise appears to come from the varying permeability of subsurface geologic features. (It is assumed that a reference magnetometer has been used to eliminate temporal shifts in the amplitude of the Earth's magnetic field). This noise is spatially correlated and has larger amplitudes at longer spatial scales. Examples of near surface total field noise spectra are shown in figure 3 for surveys at four different sites. The spectra are plotted versus frequency but represent one-dimensional spatial cuts at each site. Although the amplitude varies from site to site all four spectra are consistent with an underlying k^{-2} falloff with spatial scale (dashed lines in the figure).

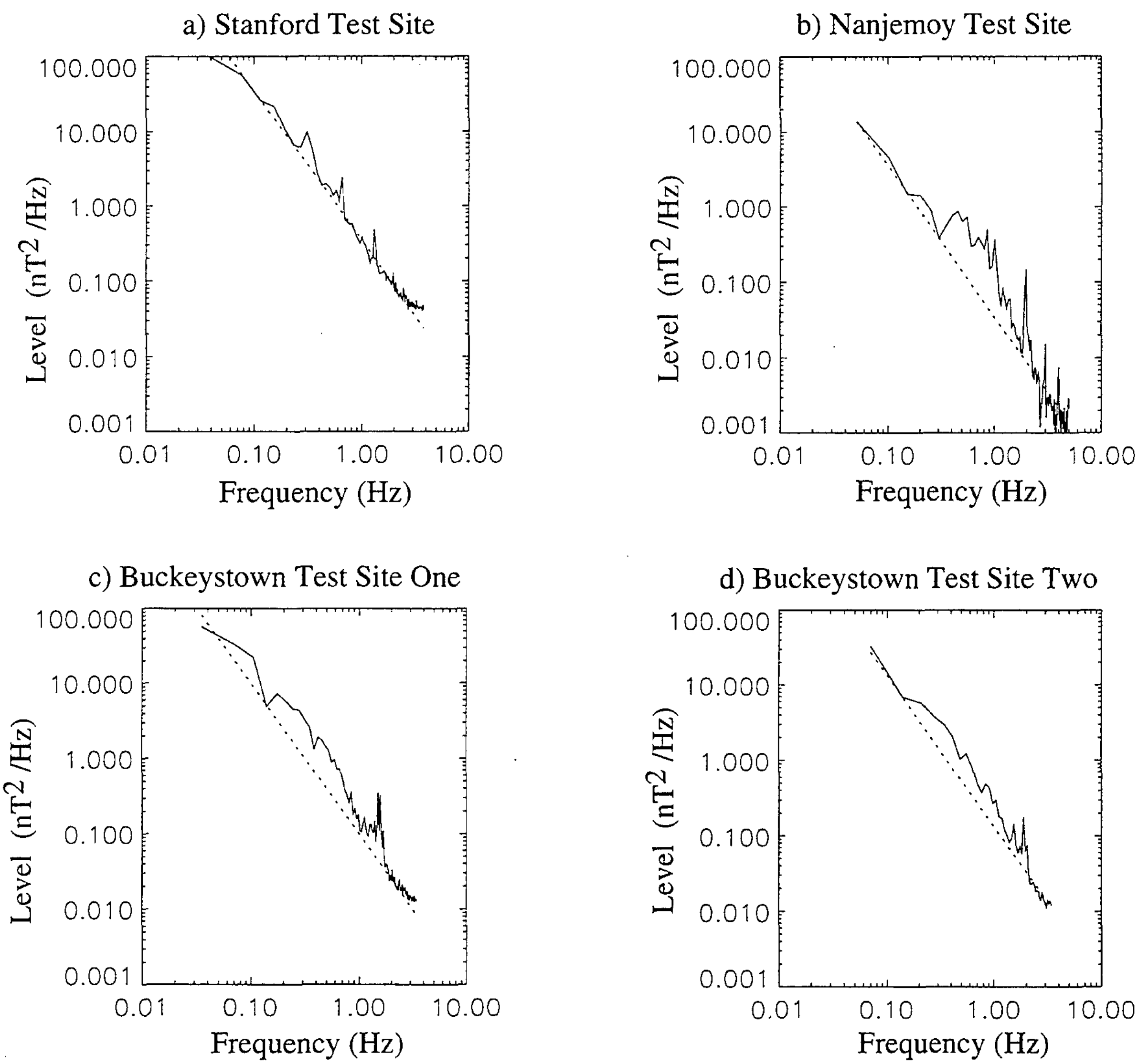

Figure 3. a) Temporal power spectral density of data taken with Geometrics type 858 total field magnetometer; b-c) Temporal power spectral densities of data taken with a Geometrics type 822 total field magnetometer.

In magnetic gradient sensors, noise due to temporal changes in the Earth field and longer scale spatial features is automatically reduced. However, the relative motion of the two sensors in field gradients introduces a new noise source which dominates for these instruments. Examples for a directional gradient sensor are shown in figure 4. The first spectra is from a survey where the instrument was held vertical. At low frequency the spectrum is white, indicating that the spatial features seen in the total field spectra are not contributing. The peak in the spectrum below 1 Hz is due to the bouncing of the sensor at each operator footstep. (The rolloff at higher frequency is due to filters in the electronics.) Data for the second spectrum were collected by swinging the instrument from side to side as the operator walked forward. This technique is often used in field surveys to "cover" the area between widely spaced survey lines. In this case the noise spectrum is dominated by peaks at the swinging frequency and at higher frequency harmonics. At low frequency the spectrum is again white.

An estimate of the expected noise is necessary in order to predict performance before a survey is performed. However, this is difficult to obtain, given the variability seen in survey data as shown in figure 3. Even if the background noise in the survey area has been well described, the performance achieved may be adversely affected by sloppy technique which increases the measured noise for a particular survey. In using the performance model for survey planning it is best to choose a range of typical noise levels and note the change in

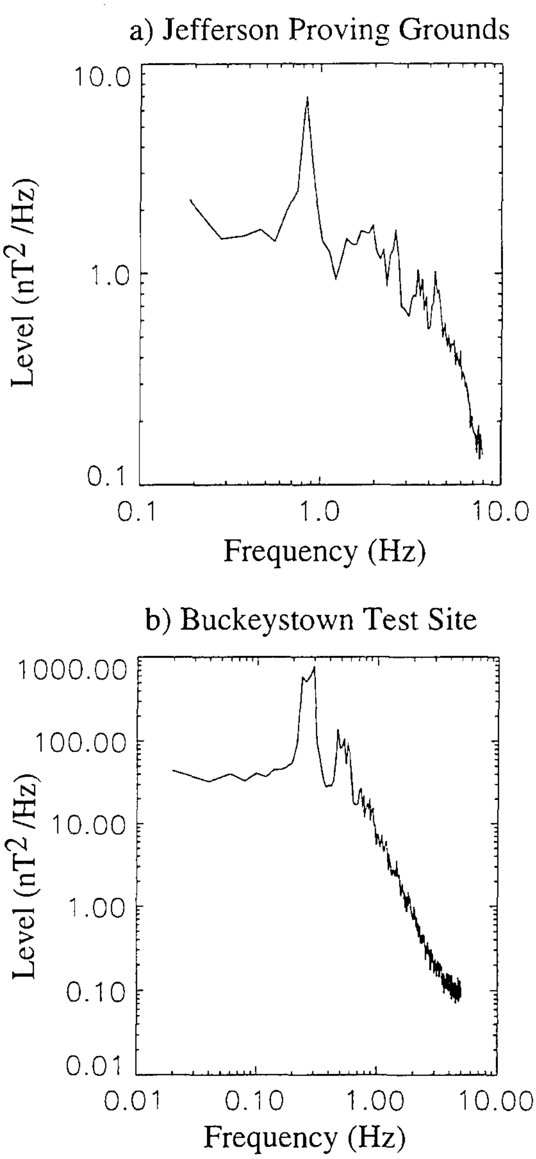

Figure 4. Temporal power spectral densities of data taken with a Schonstedt GA72 gradiometer. a) instrument vertical, b) instrument swung side to side.

performance as the level changes. If the model is used to verify performance after the survey, then the measured noise should be used.

The model for the measurement process consists of a set of positions which are representative of the locations of independent measurements under the survey protocol. The height of the sensor above the ground surface is added to the object depth to produce the total sensor distance from the object. For a typical survey which involves measurements along parallel tracks, the model incorporates the density of measured points along tracks and the intertrack spacing. These distances can be used to define a parallelogram which represents the "unit cell" covered by each measured point as shown in figure 5a. The peak of the measured signal may be at any point in the parallelogram with equal probability. The measured amplitude will depend on how large the unit cell is relative to the spread of the signal peak, and on the location of the peak. The dipole signal spreads out as distance to the source increases; for a given unit cell, the probability of measuring an amplitude near the peak amplitude is greater for deeper objects than for shallow ones. The measurement model calculates the probability of measuring an amplitude greater than some threshold value by varying the location of the peak within the unit cell. An example is shown in figure 5b for a magnetometer survey with 5 foot lane spacings and 0.5 foot spacing between measurements along the line. Here we plot the probability that a measurement will exceed threshold versus the threshold level (which has been normalized to the peak signal amplitude) for a single pass over the object. Three lines are shown in the figure for objects: shallow (sensor to object distance much less than the lane spacing), medium (distance a little less than the lane spacing) and deep (distance greater than the lane spacing). All of the curves start with a zero probability of measuring exactly the peak signal and rise to a probability of one for measuring a signal which is some fraction of the peak. For shallow objects the signal amplitude falls appreciably at the edges of the unit cell and one may measure only 5 % of the peak signal amplitude during a single pass over the object. The probability of detecting such objects is strongly dependent on the probability of encountering the larger amplitude part of the signal. This will increase the width of the critical surface for shallow objects. Once the distance to the object reaches the lane spacing the probability of encountering a signal near the peak is larger and increases swiftly for deeper objects. In planning surveys it is good to keep the lane spacing no wider than the distance from the sensor to the shallowest objects that need to be detected.

In some cases the unit cell must be increased to encompass several measurement points. This is necessary if the survey geometry is not regular from point to point, as when the survey instrument is swung from side to side. In this case the unit cell is increased to a size which encompasses all of the typical variability. We still model the fraction of the time that a given measurement point exceeds a percentage of the peak signal. Another reason for increasing the unit cell is if the detection processing requires multiple points. In this case the unit cell must be large enough to encompass all the points used.

To complete the performance model it is necessary to combine the previous information with a model for how detections are declared. In many cases a detection is declared if one, or several adjacent, measurements exceed a threshold level. For this situation the detection model simply looks for points with amplitude greater than the threshold. In other cases signal

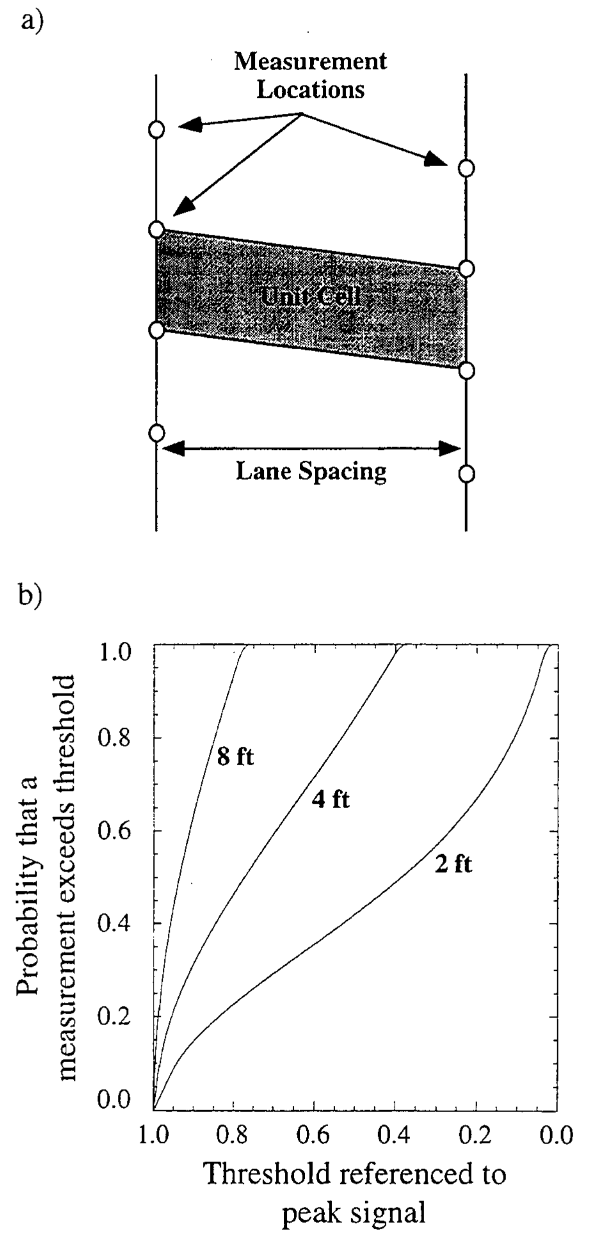

Figure 5. a) Schematic diagram of measurement model showing unit cell. b) Probability of a threshold exceedence versus threshold, for three object depths and a lane spacing of 5 feet.

processing may be performed to increase the SNR before detection. Then this processing must be modeled as well.

The selected or measured noise is used to estimate thresholds for the detection processing. For total field sensors the noise typically increases at long spatial scales. If the detection processing takes account of the varying noise level then the model must also. For instance, if the detection processing is done by a human operator the proper noise level for each spatial scale (the scale of the target signal depends on its depth) will be used. In the model it is then necessary to change the detection threshold with target depth. If the detection is performed with a single threshold, that level can be used in the model.

To make a performance estimate the operator chooses what range of size/depth space to cover and at what resolution. At each size/depth combination the appropriate signal model (total field or gradiometer) is called to estimate the signal at the sensor height. A number of trials are performed with the location of the object moved randomly throughout the unit measurement cell, and with random noise (from the noise model) added to the signal model at each measurement location. For each trial the detection criteria are checked to determine if a detection would have been declared with those data. The fraction of trials with detections at each size/depth point is the output of the performance model. These performance estimates are displayed in images of detection probability versus size and depth, as shown in figure 6 for one of the examples below.

EXAMPLES

In this section we compare the detection estimates from the performance model to detection results obtained in three field surveys.

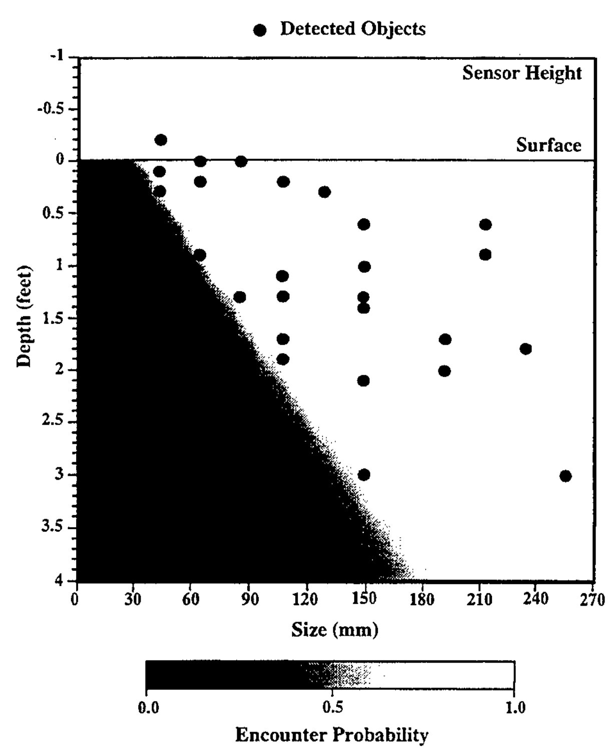

Figure 6. Performance model estimate of detection probability as a function of size and depth with detected objects; for example survey 1.

The instrument used in the first survey was a Schonstedt model GA-72 magnetometer. This instrument measures the gradient of the magnetic field component along the axis of the sensor. The gradient is determined from two fluxgate measurements separated by approximately 40 cm. For this survey the operator held the instrument vertical while walking 50 foot long lanes with 1 foot separation. The average sensor height was 1 foot off of the ground. The noise level in the data was 4 nT rms. (Although the instrument is a gradiometer we will refer to the output in magnetic units (i. e., nT) where the units "nT per sensor separation distance" should be understood). This noise level, which is much larger than the quoted instrument sensitivity of 0.5 nT, is mostly due to the bouncing motion of the instrument.

Figure 6 shows the performance estimates for this survey along with the survey results. The critical surface is quite narrow in this case, even at shallow depths. This is because the lane spacing equaled the sensor height; the signals from surface or deeper objects, that would otherwise have been visible were always encountered. In this survey we would expect to find UXO larger than 40 mm at the surface, and larger than 190 mm at a depth of 4 feet.

In this case the ground truth for emplaced objects was not available, so the survey results are represented by dipole fits to all detected anomalies. The open circles are placed at the fitted size and depth. These results show objects detected right up to the critical surface, and no detected objects with smaller size or larger depths. This is consistent with the model. The fact that the observed detections go right up to our expected detection limit implies that there were some items emplaced below the critical surface which were missed by the survey. Although we know that no objects were detected below the critical surface, we do not know if some objects above the critical surface were not detected.

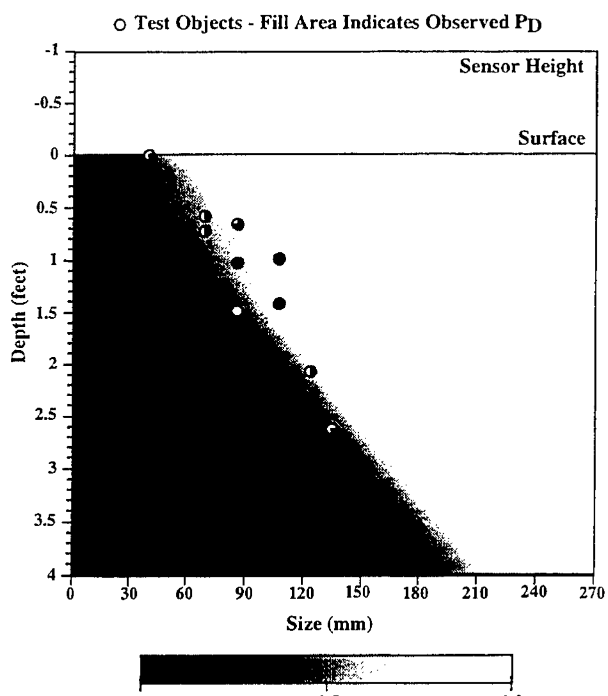

Figure 7. Performance model estimate of detection probability as a function of size and depth with detection results from example 2.

The second example survey also used a Schonstedt model GA72 magnetometer. In this case the operator swung the sensor side to side while walking forward along lanes separated by 5 feet. The sensor elevation averaged 1 foot from the ground. There were about 30 ferrous items emplaced in the field, from the surface to depths of 2.5 feet. Their sizes were meant to simulate UXO in the range of 40 mm to 130 mm. The noise level seen in the data was 7 nT rms. This is larger than is usual for this sensor and reflects the increased variation caused by swinging the sensor and thus changing the direction of the gradient measurement relative to the Earth's field.

Performance estimates and detection results for this survey are shown in figure 7. The critical surface has moved towards shallower and smaller objects, compared to the previous example, because the noise level is higher. The width of the critical surface is also distinctly wider. The extra width results from the wider lane spacing used in this survey. Even with the swinging motion the sensor can still miss objects due to coverage gaps. For objects at depths greater than the lane spacing (not shown in the plot) the probability of missing the signal decreases rapidly and the width of the critical surface narrows back to that seen for the first example survey.

The circles in figure 7 represent the detection results for two passes over the seeded field. Each circle is located at the known size and depth of seeded objects. The fraction of fill in the circles shows the fraction of those objects detected. All of the objects were seeded along the critical surface. As one moves across the critical surface from higher to lower detection probabilities, the detection results range from all targets detected to none. The detection probabilities observed agree strikingly with the performance estimates.

The third example survey used an array of four Geometrics model 858 total field magnetometers on the Subsurface Ordnance Characterization System (SOCS). This survey was performed on a seeded test field at Tyndall AFB. The spacing between magnetometers in the array was 20" and their height was 20". SOCS was run so that the spacing between the port sensor on one lane and the starboard sensor on the next lane was also 20". The noise level for this survey was 6 nT (these data were recorded in March, 1995; the noise level for typical

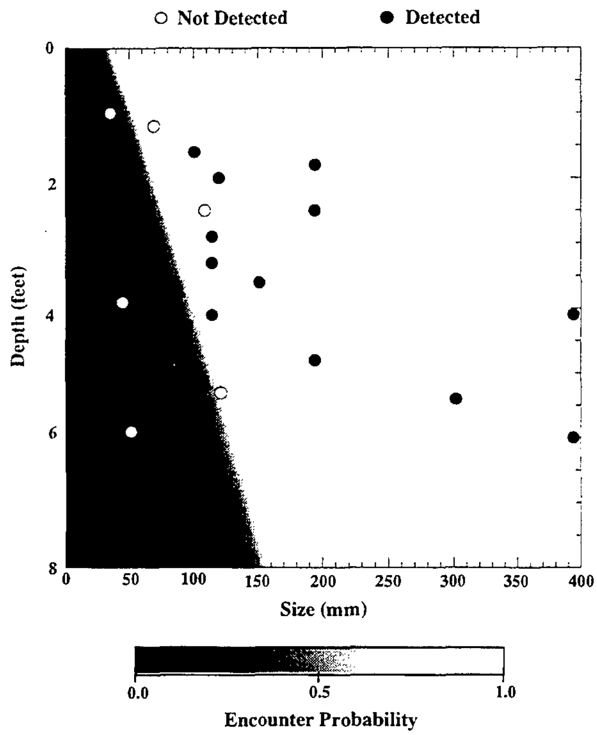

Figure 8. Performance model estimate of detection probability as a function of size and depth with detection results for example 3.

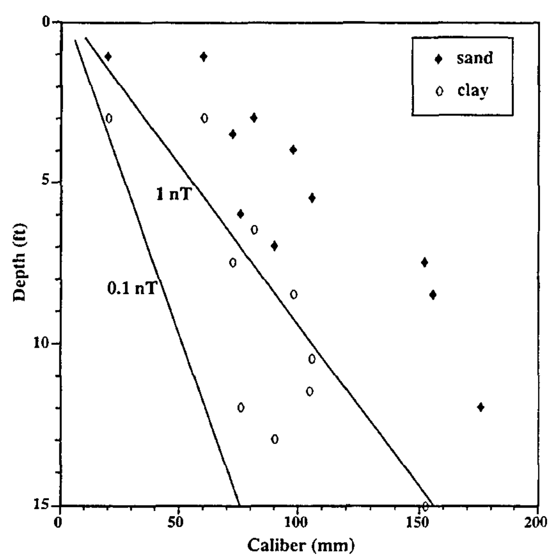

Figure 9. Estimated maximum penetration depth for ordnance in clay and sand. Solid lines are size/depth points with a maximum signal of 1 nT and 0.1 nT.

SOCS surveys has been reduced since then).

The performance estimates and detection results are shown in figure 8. Note that the horizontal and vertical scales are changed from the previous plots because larger and deeper objects were used in this data set. The width of the expected critical surface is narrow for this survey since the sensor spacing equaled the sensor height. The detection results are again shown by filled circles placed at the recorded size and depth of the emplaced objects. Filled circles indicate that the object was detected, open circles that the detection was not declared. In general the performance estimates agree well with the data. All of the objects below the critical curve are not detected and most of those above the curve are detected. There are however two points which are above the critical curve, but which were not detected (using the detection criteria that went into the performance model). The reason for this discrepancy is not clear. As mentioned previously there are several parameters which are averaged over in reducing the model parameterization to size and depth. It may be that for these objects the actual orientation and aspect ratio conspire to produce a significantly reduced magnetic signal. Or it may be that the ground truth for size or depth may be in error. We will check the ground truth for these objects to try to ascertain the cause of their anomalously low magnetic signals.

The model performance estimates and survey detection results are in good, albeit not perfect, agreement. What do the performance models tell us about magnetometer surveys? The primary conclusion is that there are regions in size/depth survey space in which UXO cannot be detected. One way to determine what is being missed would be to compare the performance plots to a distribution of penetration depths of typical UXO. We can compare the model estimates to estimates of the maximum penetration depths for ordnance (PRC, 1994). Figure 9 shows these estimates of maximum penetration depths for two soil types plotted versus size. The two solid lines on the plot are at maximum signal amplitudes of 1 nT and 0.1 nT. This is the effective detection threshold level which would have to be reached to assure routine detection of these UXO at their maximum penetration depth.

The lower amplitude (0.1 nT) is within the quoted instrument noise levels for cesium vapor total field magnetometers. However, this level is much lower than the noise levels observed in the example surveys. (The noise levels quoted for the example surveys are not the lowest possible with current techniques, but they are representative of typical field work.) This extra noise comes from environmental sources, from motion of the sensors in the Earth's field and from other sources in the data acquisition system. The achieved performance depends on the measured noise not on the instrument sensitivity. The gap between instrument sensitivity and observed noise indicates that proper auxiliary measurements and data processing will enable improvement over current performance without change of sensors (in fact improving instrument sensitivity, without attacking the noise will not improve survey performance).

CONCLUSIONS

A model for estimating detection performance in magnetometer surveys has been presented and demonstrated using data from field surveys. The total performance model consists of parts which model the magnetic signal, measurement noise, measurement locations and detection processing.

The signal model averages over variation due to object orientation and aspect, and retains the dominant dependencies on object size and depth. The magnetic signal of UXO is so strongly dependent on these parameters that we may define a narrow critical surface in size/depth space for a particular survey. Below this surface (deeper or smaller) objects can not be detected, while above it (shallower or larger) objects can be detected without difficulty.

Noise has the effect of shifting the critical surface. Increased rms noise shifts the critical surface in the direction of shallower and larger objects. However, the steepness of the change in signal amplitude with these parameters also means that significant changes in the noise are required to move the critical surface significantly. Total field magnetometers generally experience correlated spatial noise with increasing amplitudes for increasing length scales. This noise makes it more difficult to detect deep objects (whose surface signal footprint increases with depth) and so bends the critical surface. Gradiometer noise is white at longer length scales and is generally dominated by motion induced noise.

The spatial resolution of the measurements affects the probability that the largest signal amplitudes from a target will be encountered. If the lane spacing of the survey is equal to or less than the distance to an object, the signal spread will be sufficiently large that the probability the survey will measure a point near the peak amplitude is near 1. If the survey lanes are larger than the distance to the object some UXO may be missed due to coverage gaps.

The model for the detection process must take into account the processing which is actually done. For instance, human operators will automatically adjust their detection threshold for red noise, while a software detector may have a hard threshold for all length scales.

Three comparisons of performance estimates and survey detection results are presented. The performance estimates are consistent with the majority of the detection data. In the three surveys, all of which included objects below the critical surface, no objects were detected below that surface. However, in one test survey two objects above the critical surface were not detected. The reason for the unexpectedly small signal from these objects has not been determined.

Given that the model accurately estimates survey performance we can use it to determine how well state of the art magnetometer based surveys do against UXO. The conclusion from this comparison is that current magnetometer surveys are blind to some potentially relevant UXO.

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AUTOMATIC DETECTION AND CHARACTERIZATION OF MAGNETIC ANOMALIES IN TOTAL FIELD MAGNETOMETER DATA

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ABSTRACT

The Areté Engineering Technologies Corporation (AETC), under contract with NAVEODTECHDIV, has developed and demonstrated an automatic processor for SOCS (Subsurface Ordnance Characterization System) for total field magnetometer data. The processor, Magproc, is a stand alone code written in ANSI standard C, for portability. Magproc, without operator intervention, operates on SOCS generated GPS navigation, sensor amplitude and motion compensation data to produce an output file containing the locations, burial depths and object sizes for magnetic anomalies in the coverage region. Although the algorithms employed by Magproc were originally developed for the SOCS array, they are sufficiently general to have applicability to other towed array and man-portable systems both in total field and gradiometer configurations.

The processor has undergone limited ground truth testing with SOCS data taken at Tyndall Air Force Base in Florida. We have found that the processor performs well against targets that are sufficiently separated. The mean depth estimation error for separated targets was found to be 1.1 ft. while target size (small, medium or large) was correctly classified 83% of the time. The mean position error was found to be 3.2 ft. and was consistent with expected GPS positioning errors. Processor performance was limited by detection sensitivity and by target confusion in regions of higher target density.

INTRODUCTION

SOCS is a remotely piloted, multi-sensor platform system that is used as a test bed for UXO detection and characterization technologies. Current sensor systems on the SOCS platform include an array of four Geometrics, Inc. 858 total field magnetometers and a ground-penetrating radar (GPR) built by Battelle and Ohio State University. Auxiliary systems on board include a differential GPS/inertial navigation capability and sensors to measure the three dimensional motion of the sensor platform with respect to the towing vehicle.

The purpose of this paper is to describe in detail the end-to-end automatic processing algorithms used in Magproc to process SOCS total field magnetometer data and to report on limited studies of processor performance against emplaced targets. In addition, processor upgrade options are presented which should improve detection and characterization performance if implemented in future code versions.

The automatic processor is organized into several major areas which are shown in Figure 1. In the first, magnetometer amplitudes, which exist as time series, are mapped to spatial coordinates (UTM). These positions are simultaneously

AUTOMATIC PROCESSOR LOGIC FLOW

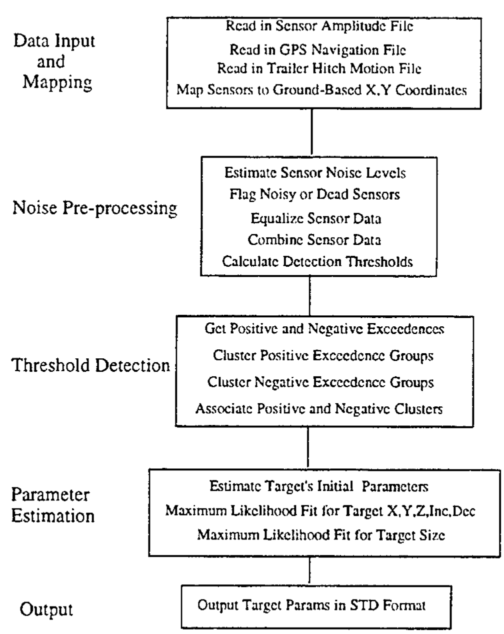

Figure 1 Main processing modules in the Magproc processor.

corrected for the motion of the platform carrying the sensors. Next, sensor median and rms noise levels are estimated using a cumulative distribution function. Sensor levels are intercompared and noisy or dead sensors are rejected. In addition, sensors are corrected for zero level and directional biases. Once an overall rms noise level has been estimated,

threshold detection is initiated. Positive and negative exceedences are then clustered separately and later associated to form target candidates. An additional algorithm is applied to resolve ambiguous associations. Upon completion of the detection algorithm, target characterization is attempted using an iterative maximum likelihood fit to a magnetic dipole model. In this step the amplitude is scaled out so only the dipole shape is fit. A second maximum likelihood fit is then done to estimate the target amplitude. The target radius is then estimated under the assumption that the magnetic anomaly is induced and the observed amplitude results from a volume equivalent sphere. Target information is then recorded in a prescribed format for future down-stream processing.

DATA INPUT AND MAPPING

The SOCS data acquisition system (SIDCAPS) produces three file streams which are necessary inputs to the automatic processor. The first stream contains the amplitudes of the four magnetometer sensors, which are sampling at 20 Hz, and an absolute time stamp. The second contains the time stamped GPS generated positions of the SOCS towing vehicle while the third contains the time stamped pitch, roll and yaw information for the sensor platform containing the magnetometers. Data for these three file types are read in and stored in three separate structures. Records from the sensor amplitude file are time-synchronized with the appropriate records from the navigation and platform files. Sensor amplitudes are then mapped to ground-based (UTM) coordinates.

NOISE ESTIMATION AND SENSOR EQUALIZATION

Before the mapped data from individual sensors can be combined and input to the target detection algorithms, noisy or dead sensors must be rejected, instrument amplitude biases removed, and an overall data noise level estimated. The algorithms to perform these tasks depend on two statistical measures: first, an estimation of the rms noise level for each sensor; and second, an estimation of the median level for each sensor. We have found that these two quantities can be extracted from a cumulative distribution function (CDF) which provides robust estimates even in the presence of strong signal contamination. This is particularly important for the rms noise level calculation which will be overestimated in environments with many targets by the standard formula. Since the rms estimate is used in threshold detection this will result in the loss of dimmer targets.

The underlying assumption in the CDF technique is that the targets represent a non-gaussian perturbation to a gaussian sensor noise field and contribute predominately to the tails of the CDF distribution. The median is extracted from the 50th percentile point of the CDF while the rms noise level is estimated by subtracting the amplitude at the 31st percentile from the amplitude at the 69th percentile. This corresponds to the plus and minus half σ points for a gaussian distribution,

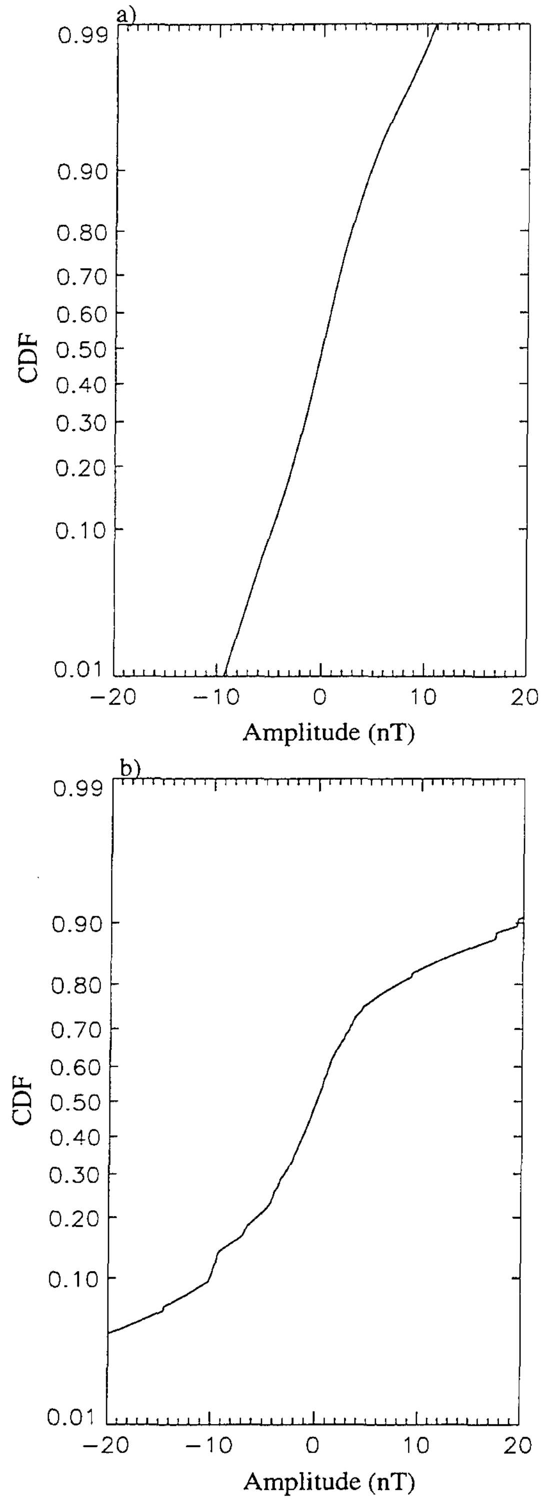

Figure 2 a) CDF of magnetometer data from Jefferson Proving Ground b) CDF of magnetometer data from Tyndall Air Force Base

away from the tails of the distribution. Figures 2a and 2b show CDFs from SOCS magnetometer data taken at two different test sites. For plotting convenience the median amplitude has been subtracted from both data sets. At the first site, from a several acre area at Jefferson Proving Ground in Indiana, target contamination is relatively small, and the CDF is roughly linear between 1% and 90%. For a purely gaussian distribution we would expect a straight line in the CDF plot. For this data the rms noise level was determined to be 2.8 nT. At the latter site, a seeded field at Tyndall Air Force Base in Florida, target contamination is heavy. Here the CDF is roughly linear only between 30 % and 70 %. However, since the rms and median are evaluated in the region of the CDF distribution from 31% to 69% we still expect the statistical estimates to be accurate. The rms noise level estimate for this site was found to be 5.5 nT.

Using the CDF technique Magproc estimates the rms noise for each of the four SOCS magnetometers. The rms levels for the magnetometers are intercompared and instruments with anomalously high (noisy) or low (poor sensitivity) levels are identified. A median sensor level is also calculated for each of the four magnetometers. This is done independently for both SOCS heading directions. This was necessary because shifts were observed, for a given sensor, between data taken in the two different directions. Shifts were also apparent between individual sensors. The median values are then subtracted from each good sensor in both heading directions, thereby, equalizing the data.

Once the sensor amplitude biases have been removed and the sensors equalized, the data can be combined into single contiguous arrays. Then, an overall noise level can be estimated and input to the target detection routine. Figure 3 shows an image of mapped and equalized data from Tyndall Air Force Base in Florida taken with the SOCS array. The field, which is approximately 150 ft. by 150 ft., was seeded with twenty two objects ranging from small pipes and ordnance to large targets such as 55 gallon drums and a 2000 pound bomb. In addition to the seeded targets a sizeable number of discrete clutter targets are visible, particularly along the left border of the image.

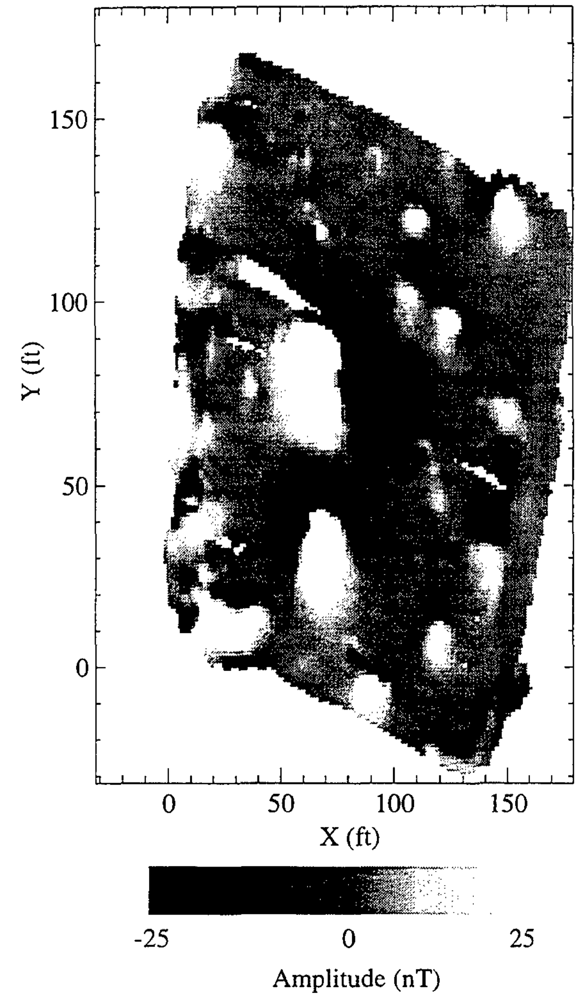

Figure 3 An image of mapped and equalized SOCS magnetometer data from a seeded field at Tyndall Air Force Base.

THRESHOLD DETECTION

Target detection begins with the application of a positive and negative amplitude threshold to the combined sensor data to identify threshold exceedences. Under the assumption that the underlying sensor noise fields follow gaussian distributions, either uncorrelated (white) or correlated (red), then the threshold levels can be adjusted, to give deterministic false-alarm and target detection probabilities. Raising the threshold levels will suppress false alarms but will also result in a loss of detections. Conversely, lowering the thresholds will allow more target detections but will also introduce more false alarms. In Magproc the thresholds are currently set at plus and minus four σ, the rms level provided by the rms noise estimator. In trials with simulated SOCS data, using four σ as a threshold, in white gaussian noise, we observed on average less than one threshold exceedence per acre. Similarly, in studies on correlated gaussian noise, we observed on average less than one threshold crossing per acre.

Exceedence Clustering

After the thresholds are applied to the data, the location and amplitude of all threshold exceedences are stored. This generally represents a sizeable reduction in data volume over the original data set with a typical reduction factor between 90-99%. The positive and negative exceedences are then separately clustered into groups of adjoining points. The cluster distance criterion is currently set to 4 ft. A point not within 4 ft. of any existing cluster will seed a new cluster. The

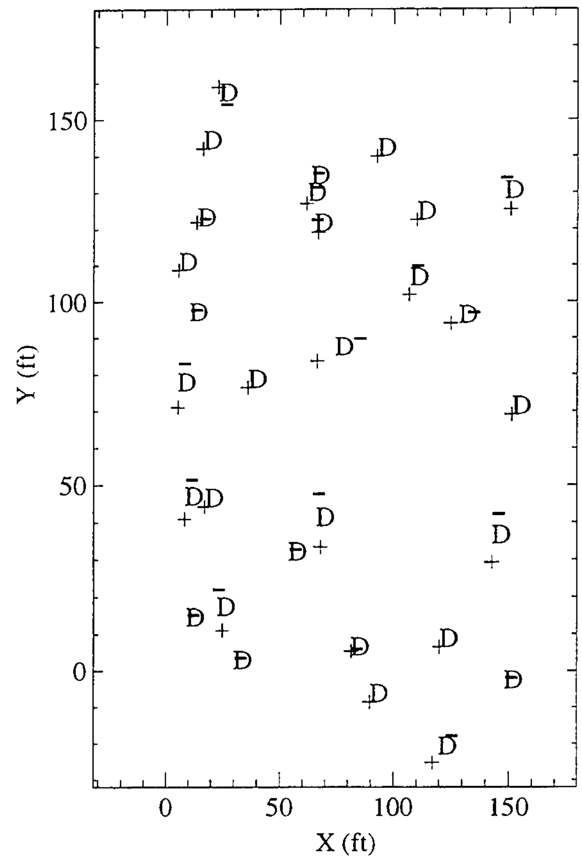

Figure 4 Shown are processor identified positive and negative cluster centroid positions, denoted by "+" and "-". Overlaid are the cluster associations, denoted by "D". The data are from a seeded field at Tyndall Air Force Base.

cluster distance criterion is a compromise value between a tighter criterion and a less restrictive criterion. A less restrictive criterion will tend to merge unrelated clusters while the former might break up a single cluster into several clusters. Problems can occur for the clustering algorithm in high density target environments where adjoining targets may appear as a single merged cluster.

Cluster Association

Magproc calculates the centroids of all clusters that have been formed for use in the cluster association algorithm. Positive and negative cluster centroids within 20 ft of each other are associated to form dipole pairs. This cut must be large enough to accommodate deeper objects whose plus and minus cluster centroids will be significantly separated. Ambiguous associations are resolved in favor of combinations with the least distance between cluster centers. Figure 4 shows the centroid positions for positive and negative clusters detected by Magproc at the Tyndall seeded field. The overlaid "D" characters are plotted to represent associated plus-minus clusters after ambiguities have been resolved. Figure 5 shows an image of data at the Tyndall seeded field. Overlaid are the estimated positions of the detected targets. The grey-scale range saturates at -25 nT and 25 nT, which are roughly the detection thresholds estimated by Magproc for this site. In both figures the target positions are initial estimates. Target position estimates are refined in the parameter estimation algorithms.

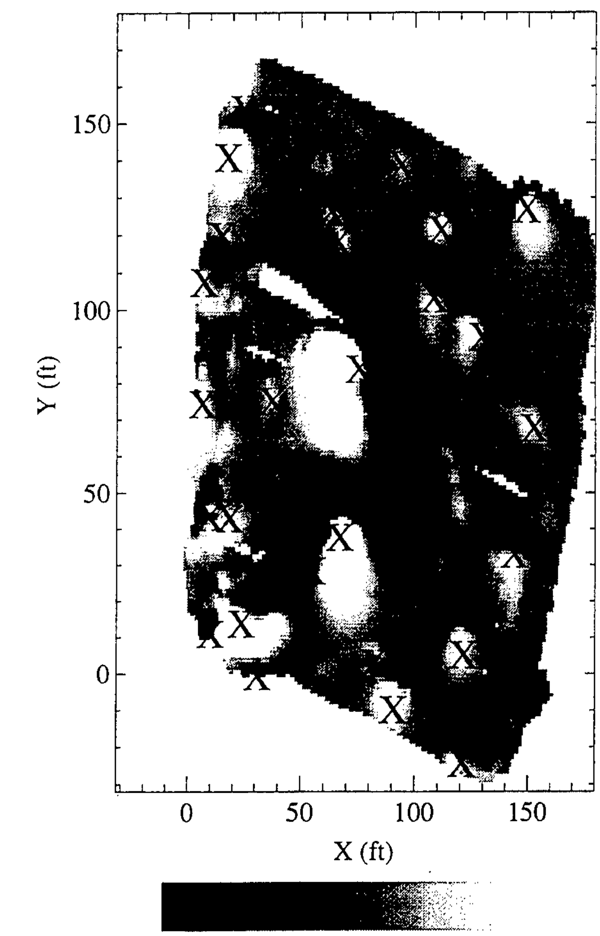

Figure 5 An image of SOCS magnetometer data from a seeded field at Tyndall Air Force Base. The overlaid "X" characters represent processor detections.

Detection Results

At the Tyndall site ten (45%) of the seeded targets were detected by the automatic processor for the SOCS data run shown in Figure 5. Of the twelve (55%) targets that were missed, eight had peak signals below the processor estimated detection threshold of plus or minus 22 nT. The remaining

four target misses came from cluster merging and mis-association to nearby targets.

PARAMETER ESTIMATION

Targets, which have been detected by Magproc, are now passed on to the target characterization algorithms. The theoretical model used for target characterization is a magnetic dipole model. The magnetic field anomaly due to a ferrous object can always be expanded in a multi-pole expansion with the leading term representing the dipole contribution. Higher order terms will fall off more sharply with distance. Thus, if the object is compact and sufficiently far from the sensor, then the dipole term will dominate. The dipole field can be written as (Landau and Lifshitz, 1960):

$$\mathbf{H} = -\frac{1}{r^3}\left(\mathbf{m} - 3\mathbf{r}\frac{\mathbf{m}\cdot\mathbf{r}}{r^2}\right) \qquad (1)$$

where $\mathbf{r}$ is the vector distance from the dipole to the point at which $\mathbf{H}$ is measured, and $\mathbf{m}$ is the dipole moment. For a solid spherical target of radius a and permeability μ, induced by the ambient earth field, $\mathbf{H}_0$, the dipole moment can be written as (Landau and Lifshitz, 1960):

$$\mathbf{m} = a^3\frac{\mu-1}{\mu+2}\mathbf{H}_0 \qquad (2)$$

For target characterization we assume that targets are solid, made of highly permeable material and roughly spherical. Most ordnance and non-ordnance, such as 55-gallon drums, are not solid objects. However, if their permeability is high and their casing thickness is greater than a couple of percent then they behave as if they are solid (Altshuler, 1996). Therefore, target size can be inferred from equation (2) in the limit that $\mu >> 1$. The size of a target in this model is therefore the radius of an equivalent volume sphere for that target and its field is governed by equation (1). Size estimates will be modified by permanent magnetization and object aspect ratio (Altshuler, 1996) which will affect both the direction and amplitude of the target magnetic moment.

Total field magnetometers measure the magnitude of the vector sum of the anomaly field and the ambient local earth field. Since the earth field is typically much larger than the anomaly field, terms involving $\mathbf{H}^2$ can be ignored. After binomially expanding the vector sum and subtracting out the local earth field, the field that the instrument measures, $\mathbf{H}_m$, can be written as:

$$\mathbf{H}_m = \mathbf{H}\cdot\hat{\mathbf{H}}_0 \qquad (3)$$

where $\hat{\mathbf{H}}_0$ is a unit vector in the direction of the local earth field and $\mathbf{H}$ is given by equations (1) and (2). Total field magnetometers essentially measure the projection of the anomaly field along the local earth field.

Target parameter estimation begins with preliminary estimates of location (x,y,z) and orientation (inclination and declination) of the magnetic dipole. At a given location the earth field inclination and declination are known and treated as known inputs. Using the preliminary estimates as a starting point, the target parameters and associated error bounds are estimated in an iterative search which minimizes the χ^2 between measured data and model predictions . In this step the dipole amplitude is scaled out so only the dipole shape is fit. If the measured data were actually due to a magnetic dipole and the measurement noise Gaussian and uncorrelated point-to-point, this procedure would result in a Maximum Likelihood estimate of the dipole parameters (Cramer, 1946). After the dipole shape is fit, a second fit is done to determine the amplitude of its magnetic moment. This amplitude is in turn converted into a volume equivalent radius.

The parameter search algorithm is implemented using a modified gradient search technique originally developed by D. W. Marquardt (Bevington, 1969). This hybrid technique combines conventional gradient search with Taylor series expansion in the immediate vicinity of the minimum. This speeds up convergence as the fit approaches the χ^2 minimum. The search is terminated when the χ^2 has changed by less than .1 % between successive iterations. If a problem occurs in fitting the data a flag is returned indicating non-normal fit termination.

Parameter Estimation Results

We have analyzed the performance of the parameter estimation algorithms on six of the ten objects detected by the processor at the Tyndall site. Two objects were removed from consideration because they were on the site coverage boundary and only partially visible. In addition, two other detections were compound objects consisting of two individual targets. These targets were closely spaced and would not be resolved individually by the magnetometers. For the purposes of target characterization we treat these compound objects as single targets and scale the expected size of the targets accordingly. For the six targets analyzed, the mean depth error was $1.1 \pm .6$ ft. while the rms position error was $3.2 \pm .9$ ft. Typical on-the-fly differential GPS measurements errors are of order 3 ft. (Hurn, 1989). We would therefore expect that a majority of position error comes

from systematic GPS error and not from algorithm error. Size classification was also studied with targets categorized as small, medium or large according to NAVEODTECHDIV guidelines. Five out of the six targets (83%) were correctly classified. The target that was incorrectly classified was associated to a fit where the depth estimate was almost two feet deeper than its actual burial depth. Since size is fit after depth, the amplitude was increased by the processor to accommodate the greater depth.

OUTPUT

If a successful fit flag is reported by the parameter estimation algorithms the target location, depth, size and size confidence are written to the output file. If, on the other hand, a fit was unsuccessful (i.e., an unstable or high χ^2fit) only the target location is recorded. This location comes from the pre-fit estimate of target location provided by the detection algorithms.

IMPROVING PROCESSOR PERFORMANCE

Processor performance at the seeded Tyndall Air Force Base site was found to be limited by a combination of detection sensitivity and target merging and misassociation in regions of higher target density. We have identified several techniques for improving processor performance.

Temporal and Spatial Filtering

Experience with total field magnetometers has shown that temporal large scale changes in field intensity are at lower frequency than the actual signals from ferrous objects, and come from remote sources. This noise source can be removed through the utilization of a stationary reference magnetometer. Since the reference magnetometer measures the same low frequency noise as the towed magnetometers, this noise source can be coherently subtracted from the data channels without affecting the target signals. A reference magnetometer is currently being integrated into the SOCS data acquisition system.

As with long scale temporal noise, total field magnetometers measure large scale spatial environmental noise. This noise source typically comes from local geology and generally has spatial scale lengths larger than those of UXO targets of interest. Contributions from these noise sources can be filtered out by high-pass spatial filtering. Since spatial noise and temporal noise typically have larger amplitudes at longer spatial and temporal frequencies (DiMarco, 1996), this, in concert with reference magnetometer integration, should significantly drop detection thresholds.

Improved Ambiguity Resolution

Currently, in the automatic processor, dipoles are formed by the association of positive and negative clusters of threshold exceedences. When this association is ambiguous, the ambiguity is resolved by a minimum distance criterion. Performance can be improved by inverting the order of ambiguity resolution and target characterization. In this scheme the ambiguity would be resolved in favor of the combination with the largest data-model fit correlation. After this combination is removed, if ambiguous pairs remained, the process would be repeated until no ambiguous pairings remained.

Improved Cluster Resolution

We have observed in regions where targets are adjoining that, in addition to having ambiguous plus and minus cluster associations, same sign clusters from separate targets can merge into a single cluster. An additional algorithm could be used to examine each cluster to see if it is consistent with the presence of a single target. A single target will produce clusters which have a peak or minimum and then asymptote to the detection threshold level. Multiple targets will make the cluster geometry more complicated by adding more nodes to the cluster surface. If this situation is detected, then an algorithm could be applied to deconvolve this cluster into multiple clusters.

CONCLUSIONS

We have developed and demonstrated an end-to-end automatic processor for the SOCS total field magnetometer array. The processor was tested on a densely seeded field at Tyndall Air Force Base with known target types, burial depths and positions. In field regions where targets were well separated the processor gave accurate depth and size estimates. Position estimates were less accurate. We attribute this to the inherent error in on-the-fly GPS measurements. Processor detection performance was observed to be limited by sensor noise levels and by target confusion in regions of higher target density. The proposed processor improvements address these issues and should lead to improved performance if implemented.

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PERFORMANCE OF ELECTROMAGNETIC INDUCTION SENSORS FOR DETECTING AND CHARACTERIZING UXO

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ABSTRACT

Electromagnetic induction sensors provide information about buried objects such as UXO that is not accessible to conventional magnetometers. We report the results of modeling and analysis of the performance of the Geonics EM61 pulsed electromagnetic induction sensor for detecting and characterizing UXO. We have used a series of controlled measurements of various test objects (metal spheres and cylinders with various conductivities and magnetic permeabilities) as the basis for a working model of the sensor response as a function of object location, depth, size, and material properties.

The model has been used to predict the instrument's ability to detect UXO as a function of size and depth. Possible instrument modifications have been tested with the model to determine the expected gain in detection as a function of size and depth.

Based on model results, characterization of an object's size and depth can be done in several ways. If the object can be identified as either ferrous or non-ferrous, the time response can be used to infer an object's size. With the EM61's present transmitter pulse, only a certain range of sizes can be discriminated. The EM61 does not currently record the time response. The spatial response can be used to infer depth based on the measured signal width. A second depth estimation can be found from the ratio of the upper and lower receivers on the EM61 (Geonics Limited, 1994). This gradient method is more sensitive to shallow depths. Again, if one assumes either a ferrous or non-ferrous object, the signal amplitude can be used to characterize an object's size once the depth is known. All of these methods assume a spherical object.

Most UXO is elongated. The shape and orientation of ordnance will affect the detection and characterization estimates. Two simple prolate spheroid models have been used to predict the signal measured by the EM61 as a function of object shape and orientation. Each model makes some assumptions about the size and distance of the UXO relative to the EM61 coils. Unfortunately, these assumptions do not cover the full range of UXO likely to be encountered; a more complete model is needed.

BACKGROUND

Based on tests conducted by the Naval Research Laboratory and GeoCenters at Fort Devens, MA (McDonald and Robertson, 1996), the commercially available Geonics EM61 was considered a viable active sensor for inclusion in the design of the Multi-sensor Towed Array Detection System (MTADS). In order to decide on a variety of final design specifications for the EM61 in a towed array system, AETC and NRL have conducted a range of tests to fully model and calibrate the sensor and, based on these results, determine its actual performance in an optimal array configuration (Barrow, 1996).

SIMPLE EM61 MODEL

Active sensors operate by transmitting a changing magnetic primary field which induces currents in any nearby conducting objects. These currents then produce a secondary magnetic field which is measured by a receiver on the sensor. Frequency domain instruments such as the Geonics EM31 transmit a fixed frequency primary field. The secondary field

is measured relative to the primary field in both amplitude and phase. The problem with this type of sensor is that the secondary field at the receiver is very small compared to the primary field. Time domain instruments such as the EM61 eliminate this problem by transmitting a pulse and measuring the secondary field after the primary pulse is over.

A simple first approach to modeling induction sensors is assumes that the transmitter field at the object is a uniform oscillating field of the form $H_0\, e^{i\omega t}$. For a spherical object, this induces currents that produce an oscillating dipole secondary field whose magnetic moment is given by:

$$\vec{m} = -2\pi a^3 \vec{H}_0 (X(ka) + iY(ka)) e^{i\omega t} \qquad (1)$$

where a is the sphere radius and $k=\sqrt{\sigma\mu\omega}$ with σ the conductivity and μ the magnetic permeability of the sphere (Grant and West, 1965). The phase of this secondary field relative to the primary field is determined entirely by the complex response function, $X(ka) + iY(ka)$, which scales as a function of the parameter $ka=a\sqrt{\sigma\mu\omega}$. The interesting aspect of this response function is that the phase of the response is given by the transmitter frequency, ω, which is known, and the properties of the sphere viz., its radius, a, conductivity, σ, and magnetic permeability, μ. It does not depend on the location of the sphere relative to the sensor.

This fixed frequency result can be applied to time domain instruments like the EM61. These sensors produce a transient pulse $H_0(t)$. To solve for the resulting secondary field $H^S(t)$, one can make use of Fourier transforms and employ the fixed frequency solution given above. The method is to transform $H_0(t)$ into the frequency domain, multiply it by the complex response function, and then Fourier transform it back to the time domain to get $H^S(t)$. Again, because the response function only depends on the properties of the sphere, the shape of the transient secondary field will not depend on its location relative to the EM61. The transient response will depend on the frequency content of the driving pulse, $H_0(t)$, and the sphere's response function over this frequency range. If this result were sufficiently sensitive to σ, μ, and a, it would be possible to determine these parameters for an unknown object simply by measuring the shape of its transient response.

The EM61 does not directly output any physical quantity given by the above model. To calibrate the model to the EM61, several factors had to be determined. The transmitter consists of a one meter by one meter square coil. The current in the coil was measured directly with a current probe. The primary field from a square coil with this current was then calculated (Y. Das, 1990). There are two receive coils with

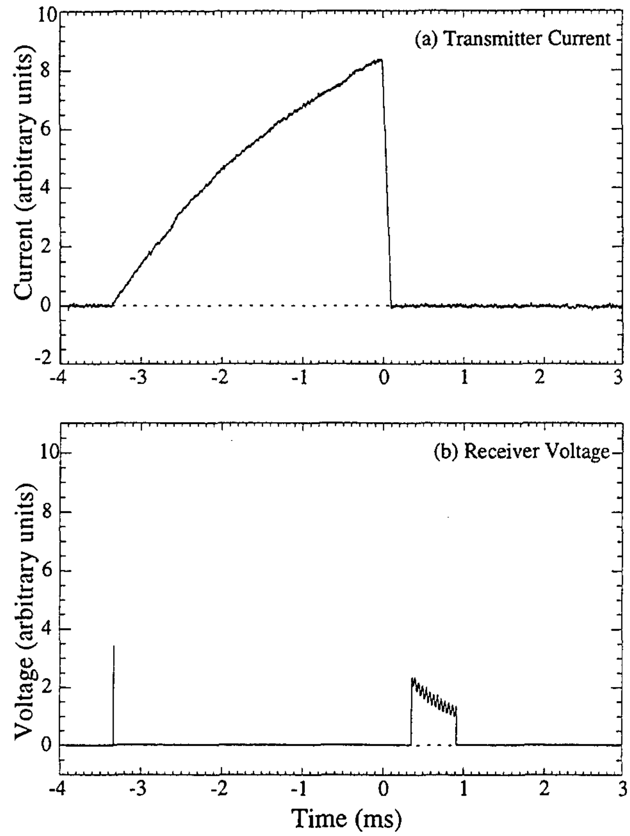

Figure 1. EM61 (a) transmitter current and (b) receiver voltage.

the same dimensions as the transmit coil. One receive coil is colocated with the transmitter coil and the other is 0.4 m above them. The time rate of change of the secondary field from the object integrated over the area of the receiver induces a voltage in the coil which is actually measured. The electronics in the EM61 gates this voltage to a 0.5 millisecond window shortly after the pulse. This gated window is integrated and averaged over many pulses to produce the typical EM61 output. The "units" of the EM61 output are reported as millivolts. To directly calibrate the model to these units, the number of turns in the transmit and receive coils is needed as well as the gain factors in the various amplifier stages of the EM61 circuit. Because these factors are not available, we have calibrated the model with a net gain factor using a known object, and checked the result against other objects.

TEST DESCRIPTION AND RESULTS

To perform these tests, the EM61 was mounted on a stable platform and various objects were moved under it in a controlled fashion. A current probe with a bandwidth of DC to 5 MHz was used to monitor the transmitter current. Figure 1(a) plots the measured pulse. The transmit pulse is 3.35 milliseconds long with a repetition rate of 75 Hz. A digital

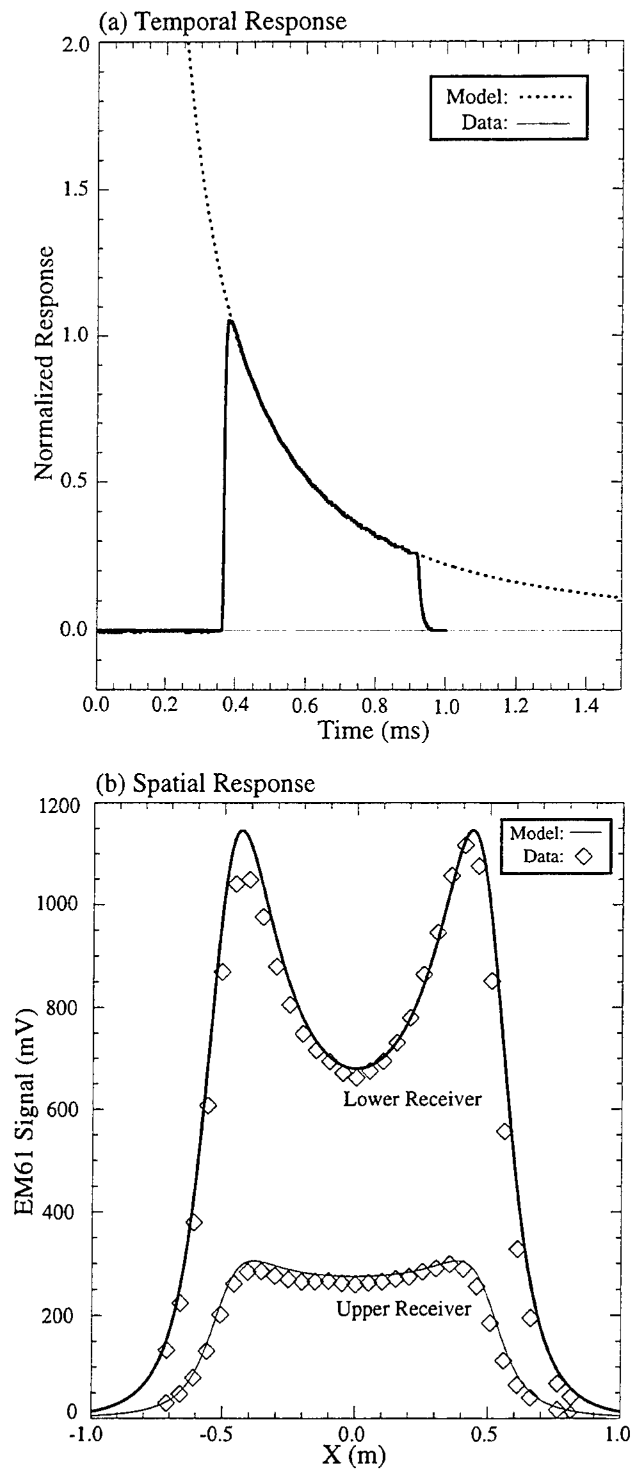

Figure 2. EM61 (a) time response and (b) spatial response to 4.875" diameter ferrous sphere 0.15 m under transmitter coil.

oscilloscope was used to measure the time gated analogue output of the receivers. Figure 1(b) shows a sample gated receiver output on the same time scale as figure 1(a). The gated window starts 0.37 milliseconds after the peak of the transmit pulse and is 0.5 milliseconds wide. The EM61 polycorder was used to record the standard instrument output for both receivers.

The object used to calibrate the EM61 model was a 4.875 inch diameter ferrous sphere (16 lb. iron shotput). Samples of the measured time and spatial response are shown in figure 2. The solid line in 2(a) shows the measured time gated data from the lower EM61 receiver. The dashed line plots the modeled time response based on the actual sphere size, conductivity, $\sigma = 1.0\times10^7$ mho/m, and relative magnetic permeability, $\mu = 500$. These time decay curves have been normalized to one at t = 0.4 msecs. The given values for σ and μ are not unreasonable for this object. The shape of the model time decay curve does not change appreciably for $\sigma = 0.5 - 2.0\times10^7$ mho/m and $\mu = 200 - 700$. The diamond symbols in figure 2(b) plot the polycorder output of the EM61 as the iron sphere was moved horizontally under the center of the sensor (x = 0). The center of the sphere was 0.15 m under the transmitter coil. The solid line in 2(b) represents the calibrated model output using all of the above parameters. This calibrated model was found to apply to a range of spherical objects from 2 to 20 inches in diameter made out of steel, aluminum, brass, and bronze and positioned from 0.1 to 1.0 m below the transmit coil.

EM61 DETECTION

The model can be used to predict the detection performance of the EM61 sensor as a function of size and depth for a given material. Most UXO and other metallic objects can be divided into ferrous and non-ferrous classes. For a given magnetic permeability, the model does not produce significantly different amplitudes for conductivities ranging from 0.5 to 4.0×10^7 mho/m. Based on these two classes, figure 3(a) plots curves of constant peak signal amplitude as a function of size and depth for nominally ferrous UXO ($\sigma = 1.0\times10^7$ mho/m and $\mu = 200$). Figure 3(b) presents the same results for non-ferrous objects ($\sigma = 1.0\times10^7$ and $\mu = 1$). A sensor height of 1.5 feet above the ground has been assumed in these curves. Typical noise levels from the EM61 are less than 1 millivolt. Objects with signal levels on the order of 1 mV or greater are readily detected, and the 1 mV curve is highlighted in both figures. Equating volume to spherical diameter, 55 gallon drums have an effective diameter of 30". From figure 3(a), drums should be detectable down to a depth of 12.5 feet. At NRL's Fort Devens test, individual drums were buried vertically at depths to center of 4.5, 7.5, 10.5, 13.5 and 16.5 feet. The greatest depth at which a drum was detected was 10.5 ft.

The model can also be used to predict detection improvement for a variety of sensor modifications. The signal strength scales linearly with transmitter current. Doubling the transmit

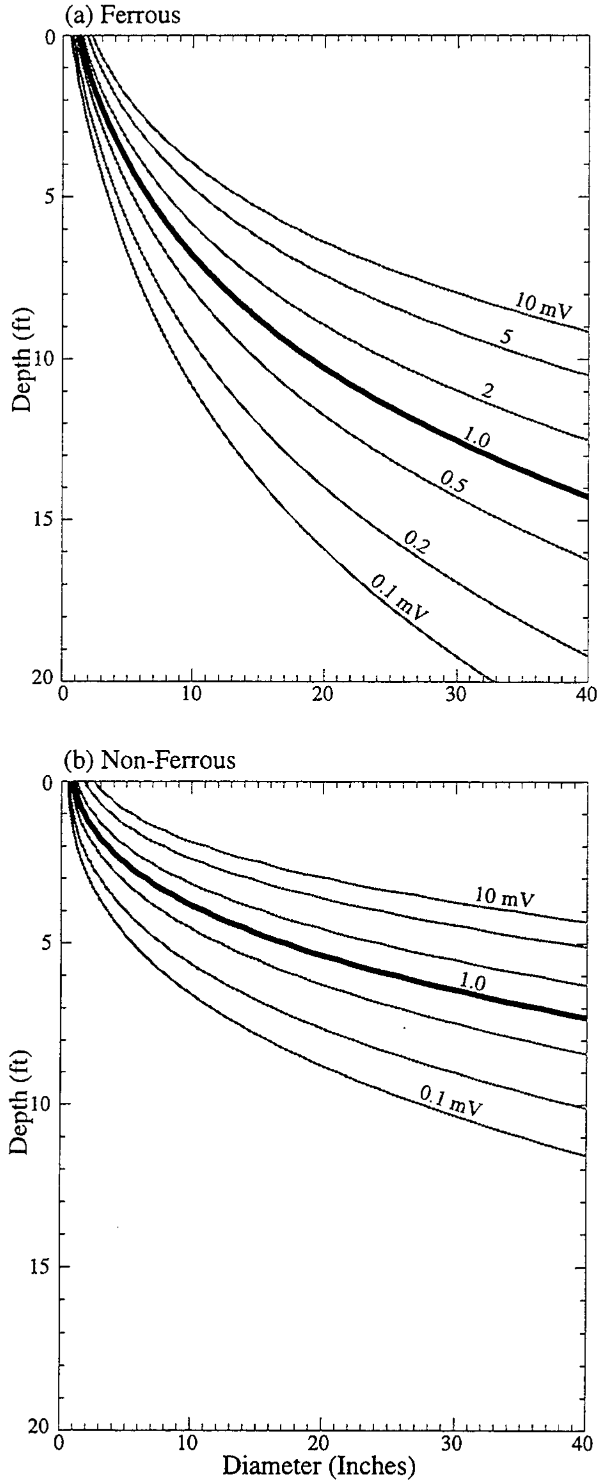

Figure 3. Curves of peak amplitude from EM61 as a function size and depth for (a) ferrous and (b) non-ferrous objects.

coil current will double the signal amplitude returned from a given object. A ferrous object with a peak amplitude of 0.5 mV in figure 3(a) would increase to a signal of 1 mV, and

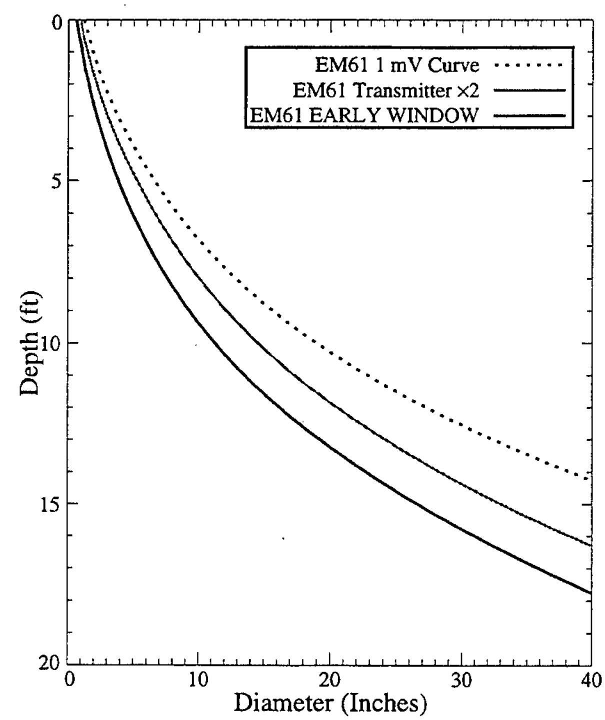

Figure 4. Change in 1 mV peak signal curve from current EM61 (dotted curve) to EM61 with doubled transmitter current (gray curve) to EM61 with earlier receive window (solid curve).

drums would be detectable down to 14.5 ft. Since the power consumed by the EM61 will change as the square of the current, this is not an efficient way to greatly increase detectability at depth. Another option is to move the gated receiver window earlier (Geonics Limited, 1996). A window from 0.15 to 0.25 msecs roughly increases signal amplitude by a factor of four from the current window. For the drum, this increases detectability down to 16 ft. Figure 4 plots the current EM61 1 mV curve (dotted line) as well as the 1 mV curve with the transmitter current doubled (gray line) and 1 mV curve with the receiver window moved earlier (black line). Other factors that could be varied are the transmit and receive coil's size and orientation. For the MTADS array of EM61's, the effect of multiple, synchronized transmit coils has been considered (Barrow, 1996). One final factor that is discussed later are the effects of object shape and orientation on detectability.

EM61 CHARACTERIZATION

The model results indicate several different ways to estimate an object's size and depth. While it is not measured by the current EM61 sensor, the time response could be recorded. The shape of the time response is only dependent on the object's size, conductivity, and permeability. Again, if objects are divided into ferrous and non-ferrous classes, a

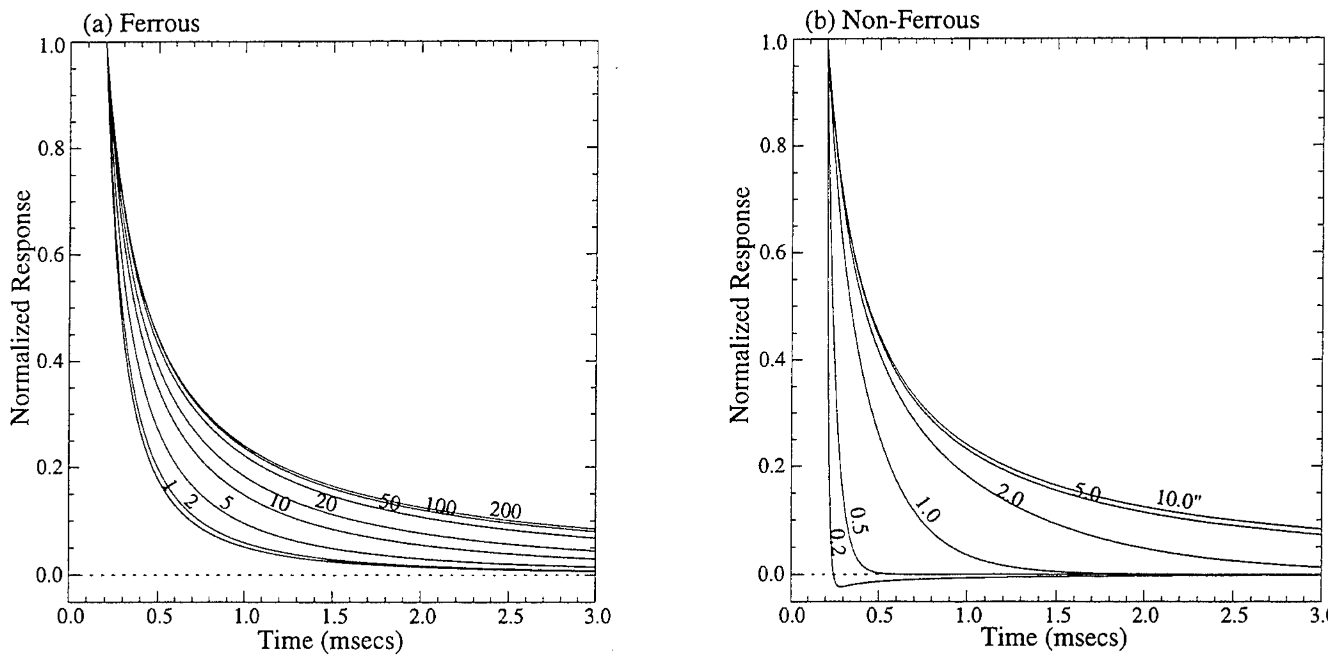

Figure 5. Normalized time response curves from EM61 transmit pulse for (a) ferrous objects ranging in diameter from 1 to 200 inches and (b) non-ferrous objects ranging in size from 0.2 to 10 inches.

different set of time response curves can be assigned to each type. The normalized time response to the EM61 pulse is plotted for a range of object sizes in figure 5. The curves are normalized to one at t = 0.2 milliseconds after the peak of the pulse. Figure 5(a) shows the response to ferrous objects and figure 5(b) for non-ferrous. The ferrous curves range from 1 to 200 inch diameter spheres, but are only sensitive to size over a range of 2 to 50 inches. Given the dimensions of ordnance from 20 mm shells to 1000 lb. bombs, this range is adequate. The curves for non-ferrous objects range from 0.2 to 10 inch diameter spheres, but are only sensitive to size up to 4 or 5 inches. At the lower limit, the response curves are dropping off so fast that they may not be measurable. These results are determined by the shape of the complex response function in equation 1 over the bandwidth of the EM61 pulse. It is possible that better size discrimination can be achieved by varying the width and repetition rate of the pulse. One interesting aspect of these time response curves is that a collection of small identical objects will produce a curve shape that corresponds to the size of an individual object, but the overall amplitude will scale with the total size of the collection. This may allow for discrimination between collections of debris and a large piece of intact ordnance.

The spatial response from the EM61 is dependent on object location, depth, size, and material properties. For spherical objects, the width of the signal as the EM61 moves directly over it is proportional to the depth of the object. Figure 6(a) demonstrates this with plots of the normalized signal for several depths. Figure 6(b) plots the Full Width at Half Maximum (FWHM) of these signals as a function of depth (a sensor height of 1.5 ft. has been assumed). The curve is linear except for shallow depths where it flattens out. Depths less than 2 ft would be hard to resolve based on signal width. The second receiver on the EM61 can be used to estimate depth as well (Geonics Limited, 1994). The curve in figure 6(c) plots the ratio of the upper receiver over the lower receiver as a function of depth. This curve flattens out at large depths and complements the previous technique well. Given a depth estimate, the amplitude of the signal is a function of size and material properties. Making the division of ferrous and non-ferrous again, a size estimate can be determined for each possibility. It should be noted that all of this is dependent on the object being spherical.

ELONGATED OBJECTS

Most UXO is elongated with an aspect ratio (length over diameter) in the range of 4 or 5. It has been noted that elongated objects do not behave the same way as spheres when measured by induction sensors (Y. Das, 1990); the shape and orientation of the object now matter. Simple models using the analytic solution for a prolate spheroid have been proposed.

The simplest approach is to use the magnetostatic solution for a prolate spheroid in a uniform field. An expression for the induced dipole moment is given by Y. Das, 1990. Figure 7 presents the results of applying this model to measurements made on an inert 37 mm shell. The shell was 3.5 inches long giving it an aspect ratio of 2.4. It was oriented vertically and positioned 0.12 m below the transmitter coil. The symbols

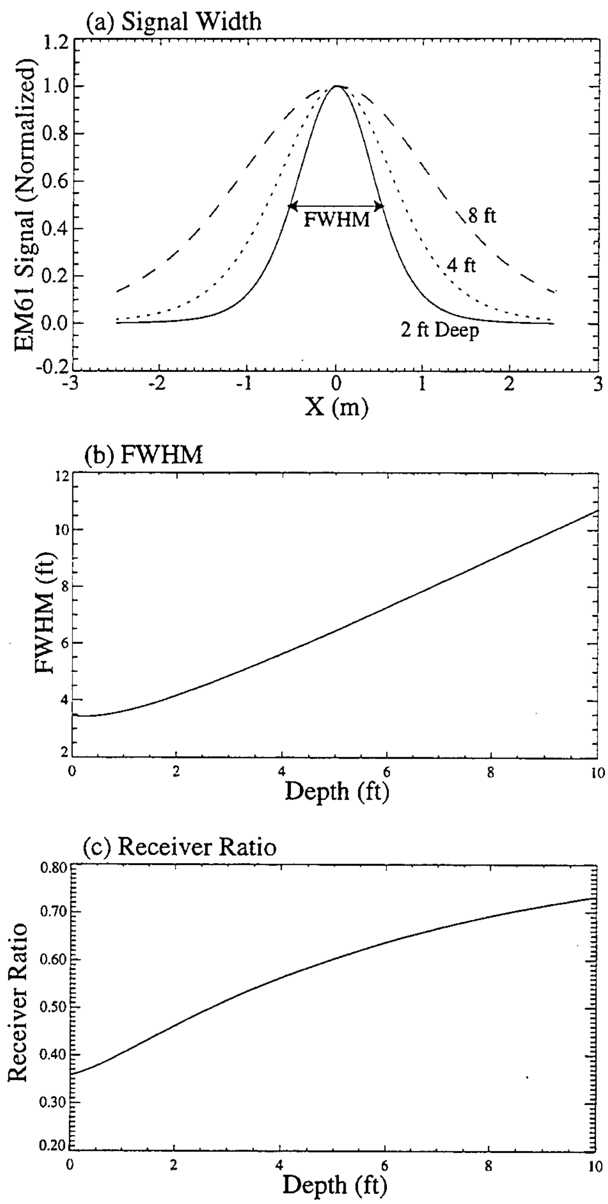

Figure 6. (a) EM61 signal profiles at increasing depths. Comparison of (b) signal width and (c) ratio of upper to lower receiver signals as a function of depth.

plot the polycorder output from the EM61. The dashed lines plot the results from the sphere model, and the solid line plots the prolate model. The prolate model provides a better fit.

This model breaks down when the object is not in a uniform field from the transmitter. For the sphere model, this does not appear to be as much of a problem because of its symmetry. As long as the sphere is at least 1 - 2 radial lengths from the coil, the assumption of a uniform field seems to apply. This is consistent with the model for a sphere in a dipole transmitter field (Grant and West, 1965). It consists of a dipole term equal to the uniform field result plus higher order moments that decay rapidly. Because of its length this is not necessarily true for a prolate spheroid. As its orientation changes from along the local transmitter field gradient to perpendicular to this, its signal changes dramatically. An analytic solution exists for a perfectly conducting prolate spheroid in a time varying dipole transmitter field (Wait, 1959). This model would be useful for objects more than 1 - 2 meters from the EM61 transmitter coil. Closer than this distance, a dipole field is not a good approximation for the field from a one meter square coil. We are currently implementing this model to compare its results to measurements of 250 and 500 lb bombs buried 5 - 15 ft. deep.

Neither of these solutions address the time response of prolate objects to a pulsed transmitter field. Because of this, the model can not be used to predict the amplitude of signals from prolate spheroids, only the signal shape. Given the usefulness of the time response curves in determining sphere size, modeling these curves for elongated objects is desirable. We are not aware of any analytic solutions to this problem and are currently considering existing numerical models that

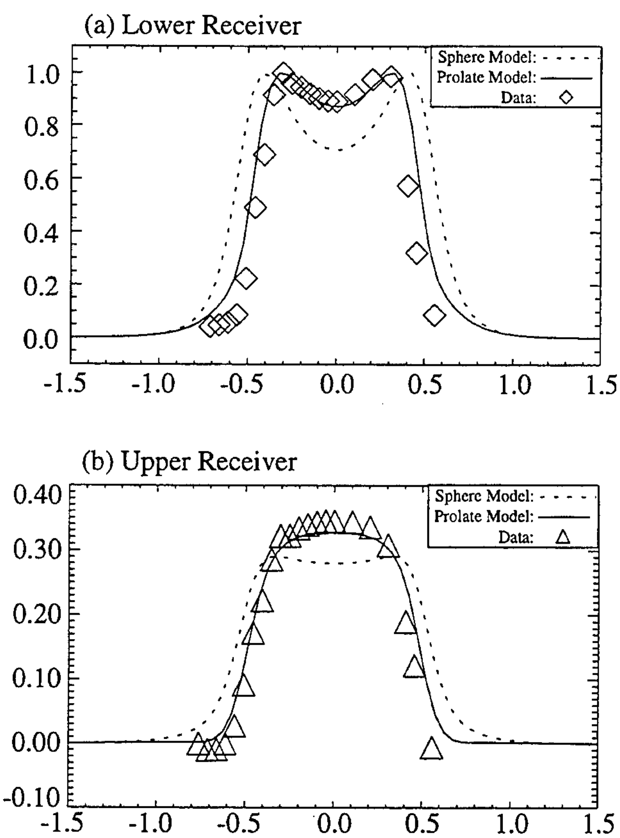

Figure 7. EM61 response of (a) lower and (b) upper receivers to a vertical inert 37 mm shell. Signals are normalized to peak value of lower receiver and compared to sphere and prolate spheroid model.

may be applied to the range of UXO dimensions relative to the size and pulse characteristics of the EM61.

CONCLUSIONS

The response of induction sensors to UXO can be modeled. Based on model results, the detection performance of these sensors can be predicted and used to determine the detection depth of a given type of ordnance. The temporal and spatial characteristics of the sensor response can be used to determine an object's size and depth. The sensor response also depends on an object's shape and orientation, so it should be possible to determine these parameters as well, given an appropriate model. It should now be possible to implement fitting algorithms for EM61 surveys similar to those currently used with magnetometer surveys using a magnetic dipole model (McFee, 1990).

The model can also be used to consider sensor improvements. For the EM61, earlier time gating has been shown to be more effective than doubling the transmitter current in improving detection performance. In terms of object characterization, changes to the transmitter pulse have been considered. Another parameter that can be studied is the transmitter/receiver coil geometry.

Besides determining the detection limits of the EM61, these results have been used to specify the survey requirements on an array of EM61's for the MTADS system (ref). Given the signal characteristics of small, shallow UXO, data sampling on foot intervals is necessary. This in turn puts requirements on the data sampling rate for a given maximum survey speed. A survey speed of 7 mph requires a data rate of 10 Hz. The ability of the EM61 to resolve closely spaced objects is proportional to its coil size. To resolve small shallow objects, would require significantly smaller coils. Unfortunately, the detection performance scales with the area of the coils. With one half by one half meter transmit and receive coils, the EM61 would measure a signal sixteen times smaller for a given object. The spacing of survey lanes and sensors in an array is determined by how fast the signal drops off if the sensor is not directly over the object. Again, to insure detection of shallow objects requires a sensor or lane spacing that overlaps the EM61 coils by one half the coil size. Finally, to operate multiple EM61's in an array requires either timing all of their pulses and receive windows to be completely separate to avoid interference or else synchronizing them completely together. The second method is easier to implement, and the effect of this has been modeled. For deeper objects, this method is advantageous in that the transmit field appears as one big coil and boosts the signal proportionally.

Both magnetometers and induction sensors are useful in surveying for ordnance. These instruments can be used to estimate an object's location, size, and depth. One last issue that requires further work is how to combine these estimates to determine these parameters better. Each sensor has advantages and problems, such as remanent magnetization for magnetometers and material ambiguity for the EM61. The presence or absence of a magnetic signal can directly address the ferrous versus non-ferrous problem of the EM61. A large size estimate from a magnetometer, but a small estimate from the time response of the EM61, would indicate the presence of many small objects. With further modeling and empirical measurements, we hope to address this problem with the MTADS system.

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MODEL BASED APPROACH TO UXO IMAGING USING THE TIME DOMAIN ELECTROMAGNETIC METHOD

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ABSTRACT

Time domain electromagnetic (TDEM) sensors have emerged as a field-worthy technology for UXO detection in a variety of geological and environmental settings. This success has been achieved with commercial equipment that was not optimized for UXO detection and discrimination. The TDEM response displays a rich spatial and temporal behavior which is not currently utilized. Therefore, in this paper we describe a research program for enhancing the effectiveness of the TDEM method for UXO detection and imaging. Fundamental research is required in at least three major areas: (a) model based imaging capability *i.e.* the forward and inverse problem, (b) detector modeling and instrument design, and (c) target recognition and discrimination algorithms. These research problems are coupled and demand a unified treatment. For example: (i) the inverse solution depends on solution of the forward problem and knowledge of the instrument response; (ii) instrument design with improved diagnostic power requires forward and inverse modeling capability; and (iii) improved target recognition algorithms (such as neural nets) must be trained with data collected from the new instrument and with synthetic data computed using the forward model. Further, the design of the appropriate input and output layers of the net will be informed by the results of the forward and inverse modeling. A more fully developed model of the TDEM response would enable the joint inversion of data collected from multiple sensors (e.g. TDEM sensors and magnetometers). Finally, we suggest that a complementary approach to joint inversions is the statistical recombination of data using principal component analysis. The decomposition into principal components is useful since the first principal component contains those features that are most strongly correlated from image to image.

1.0 INTRODUCTION

The utility of the TDEM method for UXO detection can be improved by recording and interpreting more attributes of the scattered wavefield. The scattered wavefield is due to currents induced in the target conductor by a primary time varying magnetic field. The wavefield is not measured directly, instead, voltages or emf's are measured in receiver coils. The voltages are induced according to Faraday's law by the time varying scattered fields. Measurements are performed in the time domain after the termination of the primary current waveform in the transmitter loop. The target conductor and ground response signals can be separated since currents from the latter decay much more rapidly than currents in conductors with the large and positive conductivity contrasts that are typical of UXO. The residual effect of the primary field can be separated since it is present only for a very short time after the termination of the current waveform. TDEM sensors (e.g. the Geonics Ltd. EM61) that have been deployed in the field over the last several years for UXO detection measure the induced voltages in only one time gate. In addition, the transmitter and receiver coils of this sensor are all in the horizontal plane. The imaging and discrimination capability of TDEM sensors could be significantly enhanced by recording measurements in receiver coils oriented in three orthogonal directions, and in many different time gates. However, effective use of these measurements would depend on the availability of an appropriate forward and inverse theory with which to interpret them. It would also be desirable to develop a formal and rational basis for designing an instrument that would provide the maximum diagnostic power for broad classes of targets. Finally, the formal inversion approach is adequate for post-processing of data, but complementary to this, it would be desirable to develop and implement an inference technique that is field robust and can operate in real-time or near real-time.

Thus, there are three major problem areas that we consider in this paper: (a) model based imaging capability *i.e.* the forward and inverse problem, (b) detector modeling (including instrument response) and instrument design, and (c) target recognition and discrimination algorithms. We describe a theoretical approximation developed by Habashy *et al.* (1993) that can be used to compute rapidly and accurately secondary fields for targets with large conductivity contrasts. This work can provide a basis for the forward and inverse theory required to address problem area (a). For problem area (b) we describe a formalism that can be used to improve the design of

geophysical surveys and instruments. The classical geophysical approaches to inverse theory for complicated problems often requires hand-on interaction (*i.e.* selection of model-norm constraints, optimal point on the trade-off curve between variance reduction and model norm, starting guess, etc.). The classical approaches provide essential insight and quantitative criteria for instrument design and target classification, but are not ideally suited for the real-time results required in the field due to lack of robustness. Therefore, for problem area (c) we discuss the use of neural nets for pattern recognition and anomaly classification. Also, we consider a statistical technique known as principal component analysis that can be used to produce compressed input training data for the net, and which may prove to be of utility for joint interpretation of data sets from differing sensor types. In section 2 we discuss the forward and inverse problem; instrument design is considered in section 3, pattern recognition approaches are examined in section 4, and issues in data processing and data representation are considered in section 5.

2.0 THE FORWARD AND INVERSE PROBLEM OF ELECTROMAGNETIC SCATTERING

Background

The most difficult challenge in modeling TDEM sensor responses is the computation of the secondary EM fields scattered by the unexploded ordnance (UXO) target. Many of the techniques developed for forward and inverse scattering computations are notoriously CPU intensive. Techniques based on linearization of the field variables are simpler and faster but limited in the range of problems they can solve. For example, these techniques can only be applied to problems that display small conductivity contrasts. Iterative techniques have been devised to overcome these problems, but there is no guarantee of convergence, and the approach requires repeated solutions of the forward problem which can be very expensive. Many of the computational techniques are based on the finite element method, finite differences, or integral equation approaches. These techniques can accurately simulate EM field behavior for wide frequency ranges and for a diverse variety of material properties so long as the discretization is sufficiently fine and the computational requirements do not exceeded the available resources. The principal disadvantage of these techniques is that they require the repeated inversion of a large stiffness matrix. This is a particularly worrisome problem for inverse scattering since in minimizing a given cost function or objective criteria, the same operation must be performed again and again.

A review of many of these computational techniques can be found in Volakis and Kempel (1995). A summary and comparison of computer codes that have been developed for geophysical problems can be found in Smith and Paine (1995). These codes suffer from the computational requirements described above. Some break down for the conductivity contrasts that are characteristic of the UXO problem, others are limited by the source-receiver geometries they can model, and others can model only a single conductor. Furthermore, all of these codes are proprietary, and would require many man-years to develop from scratch.

The Born Approximation and the Extended Born Approximation

The Born approximation is a scattering method that is widely used in acoustics, seismology, quantum mechanics, and electromagnetics (e.g. Wu and Toksoz, 1987; Zhou, 1989; Zhou *et al.*, 1993). The key to this approximation is that the electric field that exists within the scatter is modeled by the electric field that would exist in the homogeneous background medium. This formulation is advantageous since the forward and inverse problem can be posed simply and computed rapidly. The disadvantage is that the conductivity contrast of the scatterer with the background medium is required to be small, whereas the conductivity contrast due to metallic components of UXO can be quite large. For example, the conductivity of steel is $\sim 10^7$ Siemens/m whereas the ground conductivity of soils range from $\sim 10^{-3}$ to 10^0. This contrast causes both the amplitude and phase of the electric field induced in the metallic components of UXO to differ greatly from the background field thus vitiating the use of the approximation. The Born approximation has found useful application in environmental EM problems where the conductivity contrasts are not nearly so large. Recently, Habashy *et al.* (1993) and Torres-Verdin and Habashy (1994) have developed an approximation called the *Extended Born Approximation.* Their formulation extends the range of validity of the Born approximation to very large conductivity contrasts, yet retains many of the numerical and analytical advantages of the Born approximation. Their work provides the means to simulate accurately the electric field internal to the conductivity distribution without having to invert the large, often full, stiffness matrix that results from solving integral-equation or finite-difference schemes.

The Inverse Problem

The Extended Born Approximation renders practical the nonlinear EM inversion problem, and has been of demonstrated utility for geophysical inverse problems (Habashy *et al.* 1995). Although the estimators to compute the internal electric field are weak nonlinear functions in conductivity, they are generally much faster to compute than the full forward problem, and are almost as efficient as the Born and Rytov approximations. The enhanced accuracy of these new estimators and the advantages described above make their application to low frequency three-dimensional inverse problems in ordnance detection and imaging ideal. Forward and inverse problems based on these estimators can be applied to scatterers with many geometries including spherical objects, rectangular parallelepipeds, rectangular cylinders, thin plates, etc. Complex models can be constructed using these simple building blocks.

In the inversion process we attempt to infer information about the properties and location of an object from measurements of a scattered field. Here, the scattered field is the secondary magnetic field induced in the scatter by the primary magnetic field. Instead of measuring the field directly, we measure the time varying flux of the field which is recorded as a time dependent electromotive force (emf) in the receiver coil. The emf is a functional of the secondary fields and the recording geometry; the exact dependence can be obtained from Faraday's law which states that

$$\nabla x \boldsymbol{E} = -(1/c)\, \partial_t \boldsymbol{B}. \qquad (2.1)$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field, and c is the speed of light. The emf is given by the integral of the above over the area of the receiver coil. By applying Stokes law we obtain

$$emf = \int \boldsymbol{E} \bullet dl = -(1/c)\, \partial_t \int \boldsymbol{B} \bullet dA \qquad (2.2)$$

so that the emf can be expressed either as the line integral of the electric field along the loop of the receiver coil, or as the time derivative of the magnetic flux across the aperture of the receiver coil. The observed emf values constitute the data used in the inversion. According to the Extended Born Approximation, the integral equation that governs the total electric field $\boldsymbol{E}$ in the frequency domain is written

$$\boldsymbol{E}(\boldsymbol{r}) \cong \boldsymbol{E}_b(\boldsymbol{r}) + i\, \omega\, \mu_o \int_{V_s} \boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}') \bullet \boldsymbol{\Gamma}(\boldsymbol{r}') \bullet \boldsymbol{E}_b(\boldsymbol{r}')\, \Delta\sigma(\boldsymbol{r}')dr' \qquad (2.3)$$

where $\boldsymbol{G}$ is the Green's function tensor, $\boldsymbol{E}_b(\boldsymbol{r})$ is the background electric field, $\boldsymbol{\Gamma}(\boldsymbol{r}')$ is the so-called depolarization tensor and contains weak nonlinear dependence on the scalar Green's function and the anomalous conductivity $\Delta\sigma$, and ω is the frequency. In the integral equation the total electric field $\boldsymbol{E}$ is represented as the sum of the background field $\boldsymbol{E}_b(\boldsymbol{r})$ and the scattered field (the integral terms). The scattered field is generated by the scattering currents (and charges) induced inside the scatterer by the interaction of the total electric field $\boldsymbol{E}(\boldsymbol{r})$ with variation of the conductivity within the scatterer and host medium. The objective of the inverse problem is to recover $\Delta\sigma$ from the observed emf's.

In general, the inverse scattering problem is non-unique and the scattered field is nonlinearly related to the scattering object. The nonlinearity complicates the solution of both the forward and inverse problems. In essence, the nonlinear dependence of the scattered field on the properties of the scattering object is due to the mutual interaction between the induced currents. The non-uniqueness arises due to incomplete data coverage and because in order to stabilize the inversion matrix it is often necessary to incorporate damping or smoothing constraints which lead to low pass images of the actual object.

In addition to imaging, a benefit of constructing the inverse solution is the ability to analyze the efficiency of the *antenna array i.e.*, the space-time distribution of TDEM observations of the scattered field. The antenna array of a TDEM detector is defined by the orientation, location, and size of the transmitter and receiver coils, the distribution and width of time windows of observation, and system parameters such as base frequencies, transmitter waveforms, etc. This leads to the design considerations in the presented in the next section.

3.0 OVERVIEW OF OPTIMIZATION PRINCIPLES FOR SURVEY AND INSTRUMENT DESIGN

General considerations

The design of any geophysical survey or instrument e.g. seismic, electromagnetic, gravity, etc., is fundamental to a successful outcome. The typical goal of maximum target resolution is often in conflict with practical requirements. Thus, survey/instrument design is a classic problem in optimization theory (*i.e.* given quantifiable objective criteria, what is the

optimal choice of instrument or survey design parameters?). There are a number of questions that should be addressed in the design process: (1) What is the optimal trade-off between redundancy of field measurements (which we seek to minimize) versus accurate characterization of the target? (2) How should *a priori* information e.g. statistically characterized noise environments, geophysical measurements from other sensors, known geology, target class, etc., be incorporated into the design process? (3) What objective criteria in the inverse problem are most appropriate to consider e.g. resolution of sub-surface voxels, delineation of boundaries, covariance between estimated model parameters, effect of design parameters on noise amplification, stability of inversion matrices, etc.? In this section we discuss the general problem of geophysical survey and instrument design, and present criteria that can be used to evaluate the efficiency of such designs. The survey/instrument design can be adjusted until an objective function defined by the criteria is maximized. This process depends on the ability to compute the forward and inverse solutions. In addition, since the objective function may be topologically complex, it is necessary to use an optimization technique capable of locating the globally optimum solution. We show that the smallest singular value of the design matrix constitutes a useful objective function, and we suggest that genetic algorithms are well-suited for discovering the optimal solution.

Barth and Wunsch (1990) have shown that inverse theory can be usefully applied to the experiment design problem. They considered the optimal deployment of sources and hydrophones for an ocean acoustic tomography experiment. Their design approach applies equally well to the design of geophysical sensors. The inverse solution determines which data contribute most to the resolution of the model parameters that characterize the problem. For example, in the resistivity inverse problem, the inverse solution determines (1) which of the measurable field quantities, and which set of transmitter-receiver separations and transmitter frequencies best resolve the conductivity and thickness values of an earth model, and (2) which combinations of data optimally mitigate noise effects. The singular value decomposition (SVD) of the design matrix provides valuable diagnostics of the experimental design. It is generally the case that the utility of the design is improved by adjusting the survey parameters to increase the condition number or the size of the smallest singular value of the design matrix. Thus, to optimize a survey design, one attempts to maximize an objective function given, for example, by the smallest singular value. Clearly, this is a strongly nonlinear problem, and cannot be solved with classical techniques. However, as mentioned above, genetic algorithms can be usefully applied to this problem

Technical Discussion - Objective Criteria

The choice of the objective function is one of the most important elements in survey/instrument design. The design will depend on the target features of interest, and on how the data will be processed and interpreted. A design that yields good performance for one set of criteria may perform less well for another. Regardless of the specific goal, objective criteria can always be framed in terms of very general functionals that are easily computed during the inversion process. Criteria can be defined in terms of subsurface volume element and boundary resolution, model parameter covariance and trade-off, noise sensitivity, matrix stability, and others.

Barth and Wunsch (1990) have shown that singular value decomposition is a useful way of computing many of the objective criteria of interest (see also an early contribution by Glenn and Ward, 1976). To demonstrate this we consider the canonical inverse problem

$$\boldsymbol{G\Delta m} = \boldsymbol{d}, \tag{3.1}$$

where $\boldsymbol{G}$ is the design matrix, $\boldsymbol{\Delta m}$ is the vector of unknown model parameters, and $\boldsymbol{d}$ is the data vector. $\boldsymbol{G}$ is dependent on the physics of the particular problem and on the detailed properties of the survey/instrument design. It is easy to see how equations (2.2) and (2.3) can be combined to yield this type of inverse problem. If there are no noise or other error terms in the data, a fully determined system would give rise to perfect resolution. In most cases however, the matrix $\boldsymbol{G}$ is singular, and instead of determining the model parameters, one is forced to estimate them. Using the SVD of $\boldsymbol{G}$, one particular estimate for the model parameters is

$$\boldsymbol{\Delta m} = \boldsymbol{V\Lambda^{-1}\, Ud} \tag{3.2}$$

where in the usual way $\boldsymbol{U}$, $\boldsymbol{V}$, and Λ are such that $\boldsymbol{G} = \boldsymbol{ULV^T}$ (Aki and Richards, 1980). $\boldsymbol{U}$ and $\boldsymbol{V}$ span, respectively, the data and model spaces, and $\boldsymbol{\Lambda}$ is the diagonal matrix of singular values λ_i for $1 \le i \le N_m$, where N_m is the number of model parameters. If the rank of $\boldsymbol{G}$ is less than N_m (the rank corresponding to the number of non-zero singular values λ_i for $1 \le i \le$

p), then there is a null space and the vector of model parameters breaks up into a piece Δm_p which is determined by G and a piece which lies in the null space Δm_0 about which no information is available. The matrix V also decomposes into V_p made up of the first p columns of V and V_0 which is constructed from the columns $(p+1)$ through of V. Then all solutions for Δm are now of the form $\Delta m = \Delta m_p + V_0\alpha$ where $\Delta m_p = V_p \Lambda_p^{-1} U_p d$ and α is a matrix of arbitrary coefficients. Different estimators of Δm make different choices for the formally indeterminate values of α, ranging from setting them to zero (for the minimum mean square solution) to employing *a priori* statistical information about the solution. From Aki and Richards (1980), the error covariance matrix is

$$<\Delta m\, \Delta m^T> = \sigma_n^2\, V \Lambda^{-2}\, V^T \qquad (3.3)$$

where we have assumed for simplicity that data errors are uncorrelated with standard deviation σ_n. Obviously, the covariance of the solution becomes large when λ_i is small. Associated with these entries will be certain elements of the estimate Δm which will be poorly determined, possibly unacceptably so. Some workers have eliminated eigenvectors with small eigenvalues to keep the covariance below a certain level. This, however, reduces the number p of non-zero eigenvectors, degrading the resolution in model and data spaces. The resolution matrix of the model parameters is VV^T so that the estimated model parameters Δm_{est} are related to the true model parameters by $\Delta m_{est} = VV^T \Delta m$. The trace of the resolution matrix VV^T equals the rank of G, and, therefore, truncation of singular values will lead to deterioration in the resolution matrix.

Noise processes represent another important factor. In the presence of noise the minimum variance estimator is a useful solution. The estimator which minimizes the trace of the covariance matrix and the covariance of this solution are given, respectively, by $\Delta m = RG^T(GRG^T + \sigma_n I)^{-1} d$ and has covariance $<\Delta m\, \Delta m^T> = V\Lambda(\Lambda^2 + \sigma_n^2/\sigma_m^2\, I)^{-2}\, \Lambda V^T$ where R is the *a priori* covariance matrix associated with the true model parameters, and σ_m is the standard deviation of the model parameters. Although the instability of equation (3.2) is reduced by eliminating small singular values, it is now important to consider the relative magnitudes of the small singular values to that of the noise term in above covariance estimate. Although the design matrix G may be such that the system is fully determined, its smaller singular values may be so small that they become negligible when compared to the noise level in the measurements. In this case, it is usually better to reduce the rank of G. Truncation of small singular values leads to a more stable estimate for the model parameters, but at the price of resolution loss.

In designing an instrument or survey for a given target class, it would seem reasonable then to try to make the rank of G equal to the rank of the system (*i.e.* N_m), and the magnitude of the smallest singular value in the spectrum of G as large as possible. If the smallest singular value is large enough, so that it is not noise dominated, then truncation would not be necessary. The covariance (eq. 3.3) for the estimate in equation (3.2) would be well behaved, and the model resolution would not be compromised. The model estimate and its covariance in the presence of noise would also not be noise dominated. Therefore, if we desire to design a system which is fully determined, then we choose the objective function F to equal the smallest singular value λ_{Nm}. The singular values of G, in turn, are related to how the geophysical fields sample the subsurface, which is determined by the distribution of the sources and receivers and instrumental parameters. If the underdetermined case is considered when perfect resolution of all the model parameters is not required, the objective function is modified to $F = \lambda_p$, where p is less than N_m and equal to the rank of G which is desired. There is yet another approach to this problem suggested by Snieder and Curtis (1995). They point out that although the ill-conditioning of the design matrix is often computed in terms of the condition number (the ratio of the largest to the smallest singular value, and which can therefore be infinite), a more useful measure of conditioning is given by $\Theta = N_m\, \lambda_1 / \Sigma\, \lambda_i$, where λ_1 is the largest singular value, and the sum is taken over all singular values. The sum in the denominator is equal to the trace of G while λ_1 may be estimated using the power method. Hence Θ may be calculated swiftly even for large, non-sparse matrices.

As shown above, the model resolution is sensitive to data error. Thus, estimates of data error can be used to asses which data attribute best resolves a given structure, and the generalized inverse can be used to determine which data contribute the most to model resolution. Study of the eigenvectors that compose V provides insight into model parameter correlations and measurement correlations which can be exploited for improving the design of an experiment or instrument. Although the most intuitive objective function may be the one which yields minimization of the mean square error in synthetic experiments using an *a priori* model, the diagnostic criteria defined

above yield other important measures that evaluate the quality of the solution such as model covariance, matrix stability, model resolution, etc.

Numerical Optimization Method

Once the objective criteria are established and can be computed numerically, it is necessary to search efficiently for the survey or instrument design that yields the highest objective function valuation, and which does not exceed the available experimental resources. In general, the survey/instrument designs can be: (1) completely random, (2) structured to the extent that the controlling parameters vary in a well defined and likely discrete manner, or (3) confined to a limited number of fixed designs. The objective function will display highly nonlinear dependence on the parameters that characterize the survey/instrument design and this presents numerical problems. In fact, the problem is so strongly nonlinear that all classical optimization techniques such as the Newton-Raphson or conjugate gradient methods would fail completely. These methods can yield solutions that are local maxima rather than the global maximum. Another problem with the classical approaches is that they required partial derivatives of the objective function with respect to the survey/instrument parameters, and the derivatives can be difficult, if not impossible to evaluate. For example, the singular value of the design matrix is clearly a strongly nonlinear function of the components of the matrix. These problems can be addressed in principle through the use of genetic algorithms, and this was the approach used, for example, by Barth (1992) and Hernandez *et al.* (1995). Although, the geophysical problems are likely to be more computationally intensive than the oceanographic problems described in the above references, the use of genetic algorithms remains appropriate.

Genetic algorithms draw inspiration from the optimization process that forms the basis of biological evolution. Evolution is a process whereby a biological species defined by order 1000-10000 genes is modified to optimally fit the present environment. Geophysical survey/instrument optimization problems can be defined by a similar number of parameters. The most serious challenge is the volume of the phase space in which to search and the complexity of the optimization surface in that space. For example, if the dimensionality of the parameter space is of order 100 with just a few possible states for each parameter, say 10, then the number of points in the phase space approaches 10^{100}! An essential feature of genetic algorithms is their ability to bypass the inefficient component of the phase space.

In their most basic implementation, genetic algorithms make use of the following simplified version of the biological evolutionary process. First, the model parameters are coded in binary form. The algorithm then starts with a randomly chosen population of models called chromosomes. Second, the fitness values of these models are measured by some fitness criteria such as agreement between data and prediction or simply the minimum or maximum of an objective function. Third, the three genetic processes of *selection*, *crossover*, and *mutation* are performed upon the models in sequence. In *selection*, models are copied in proportion to their fitness values based on a probability define by the value of the objective function divided by the sum of the objective functions over all models. In *crossover*, an operator picks a crossover site between selected pairs of chromosomes and exchanges, based on a crossover probability, the bits between the two models. In *mutation*, a bit is changed at random based on mutation probability, and is applied to the models to maintain diversity. After execution of the above processes, the new models are compared to the previous generation and accepted based on an update probability. The procedure is then repeated until convergence is reached (*i.e.* when the fitness of all the models becomes very close to one another). Useful discussions on the use of genetic algorithms can be found in Charbonneau (1995) and Sen and Stoffa (1995).

Once the TDEM sensor is optimally designed for prescribed target classes, one can expect the performance of target recognition algorithms to improve, which leads us to the next section.

4.0 TARGET RECOGNITION ALGORITHMS

TDEM sensors display a rich spectrum of responses to metallic conductors. The response is dependent on the properties of the scatterer, the nature of the excitation, and on the manner in which the scattered field is measured and processed. As discussed in section 2, the detector response can be characterized mathematically and the inverse problem can be formally posed. This approach is useful since it allows one to discover the types of data and the instrument parameters that usefully constrain the target. In practice, formal inverse problems can be made robust for well-defined and well-rehearsed problems. However, for actual field deployments in which there are highly variable field and noise conditions, and

real-time or near real-time imaging requirements, the implementation in the near future of an inversion process that does not require interfacing from the expert user would be rather difficult. (We expect, however, that post-processing with the formal inverse method will be practical). Accurate estimation of model parameters using any kind of sensor (not just TDEM) can be a very difficult problem. Ambiguity arises through insufficient or noisy data. This leads to non-uniqueness that can only be resolved by *a priori* constraints such as positivity, compactness, smoothness, small model norm, etc. Further, any inversion is limited by the accuracy and/or assumptions of the theory used to interpret the data. Lastly, ambiguity arises from the nature of the non-linear inversion itself, *i.e.* the iterative inversion procedure may not converge to the correct solution. These types of problems motivate the use of neural networks for the UXO inverse problem. We suggest in the following that the complete solution of the formal forward and inverse problems informs the development and routine use of the neural network approach.

Raiche (1991) presents an excellent overview of the application of neural nets to problems in geophysical inversion. He describes the shortcomings of the classical techniques including some of the points mentioned above. Raiche describes a paradigm for an automated geophysical system which works like a noise tolerant, interpolating associative memory; *i.e.* given raw geophysical data from one or more types of surveys, it will output a representation of Earth properties which gave rise to the input data structure. He goes on to list the desirable attributes that the system should have. Since these are precisely the attributes that a field robust TDEM detector should have, we quote directly from his paper:

- The system as a whole should be able to extract and classify features of the input data structure, and establish rules associating their interrelationship with observed Earth structure models.
- It should be able to utilize data sets from different geophysical methods by establishing rules governing the relative weighting of various data features.
- It should be able to learn from experience. In this case the experience will comprise all of the numerical and analogue model and field data curves along with whatever interpretations have been input to the system.
- It should be able to infer (develop) a suitable noise model so that the shape of the class boundaries will encompass distorted members of the same class. In other words, it should be capable of mapping input data into a nonlinear space with a metric which minimizes the effect of observed noise.
- It should be stable; i.e., given the same input data sets, it should infer consistent interpretations. It should not 'forget' or distort prototypes.
- It should be capable of inferring model structures not necessarily contained in the training set; i.e., it must be capable of interpolating within the metric established by noisy prototypes.
- It should not be bound by local error minima traps when comparing field data with forward model data from the final model.
- It should be computationally efficient.

The design of an inversion process based on a neural net that displays the above desirable properties is a challenging problem. Broadly speaking, there are three major problem areas that must be addressed, and we refer to these as Task 1, Task 2, and Task 3.

Task 1: The first task is to choose an appropriate interpretation space for the inversion results. By this we mean the characterization of the net's output layer. A very general characterization would be the representation of the subsurface with discrete 3D voxels; each node on the output layer would correspond to a single voxel. The classifier would then assign properties to each voxel. As Raiche (1991) points out, an alternative would be to implement a two-stage output process. The first stage would classify the data as arising from a specific model class; e.g., ant-personnel mine, anti-tank mine, etc. The second stage would consist of estimating the parameters associated with the model class, e.g. depth of burial, location, orientation, etc.

The appropriate choice of output node classification can benefit from thorough consideration of the forward and inverse problem. This follows from the fact that the solutions to most practical inverse problems are non-unique. There are some properties of the unknown model that simply cannot be retrieved from the data (Aki and Richards, 1980). Furthermore, it is generally not possible to obtain point estimates of the model. Instead, the inverse solution can only retrieve certain averages of the model, and this defines fundamental limits of resolvability. The formal solution of the inverse problem defines what model properties can be retrieved. It is these properties that should be used to characterize the output layer. Further, as discussed in section 3, the inverse solution determines which components of the data contribute most to the resolution of the model. Such knowledge can be used to tailor the input layer. Finally, an important benefit of developing the

forward model is that training data can be computed synthetically for arbitrary UXO targets and instrument parameters. This can yield significant cost savings over data training data collected in the field.

Task 2: A crucial task is the development of the appropriate representation for the input geophysical data. The input data should be of minimal dimensionality and represented in such a way as to optimize feature extraction. We suggest in section 5 that the principal component transform can be used to achieve some of these objectives. It can be applied to data sets from multiple sensors (e.g. TDEM sensors and magnetometers), or to a data set in which many realizations of the same signal in a noisy environment are available.

Task 3: An important task is the development of a mapping algorithm capable of transforming a suitable representation of the input data into a description of the UXO target. There are many existing neural network architectures and training algorithms to choose from, and it is likely that the best algorithm can only be discovered by experiment.

5.0 SIGNAL PROCESSING AND DATA REPRESENTATION

In this section we consider the utility of principal component analysis for TDEM processing. The principal component transform is a versatile tool. Although we present here how it may be used to enhance the signal to noise ratios of TDEM responses, we have also used it successfully for spatial processing of geophysical data sets collected with different sensor types. The mathematical treatments for these two different cases are identical. In the following we consider the TDEM response at successive multiple time gates to represent a time series which can be thought of as a vector. Likewise, a two-dimensional spatial image can also be represented as a vector.

Data collected with TDEM sensors can be evaluated statistically since many recordings are obtained for a single location in space. This is due to the base frequency of the waveform which can vary from a few Hz to a 1000 Hz, or more. For a TDEM instrument that performs measurements in more than one time gate, each recording will correspond to a time series. There will generally be correlations among each realization but noise is always present. However, by using the covariance properties, it must be possible to extract those features that are coherent across the data sets, to facilitate noise rejection, and to segregate uncorrelated features. A particular transformation known as the Karhunen-Loeve transformation achieves these objectives. The Karhunen-Loeve transformation is also known as the principal component transformation, the eigenvector transformation, or the Hotelling transformation. Discussions of this class of transform can be found in Fukunaga (1972), Ready and Wintz (1973), and Andrews and Hunt (1977). This method can be applied equally well to a set of spatial images, or to a set of time series, and essentially represents a form of 'smart stacking'. One way to achieve the decomposition into principal components is by performing an eigenvalue-eigenvector decomposition of the covariance matrix, and then rotating the original input data vectors using the eigenvector matrix. We show in the following that the same effect may be achieved by constructing the singular value decomposition of the input data matrix. The advantage of the SVD approach is that it greatly illuminates the meaning of the principal component transformation, and it is computationally efficient and stable.

In essence, the transform decomposes the input data set of time series into an orthogonal set of time series that we call eigenseries. The eigenseries associated with the largest singular value of the data matrix includes those features with the greatest variance and that are most strongly coherent across the original input time series. The eigenseries associated with the intermediate singular values rejects those features in the input data sets that are highly correlated as well as highly uncorrelated. The eigenseries associated with the smallest singular value contains those features that are least correlated across the data sets, and often includes a strong noise component. Thus, the principal time series corresponding to the largest singular value represents the desired result of a smart stack.

The Singular Value Decomposition Approach to the Principal Component Transform

It turns out that the principal components obtained from the Karhunen-Loeve transformation are identical to the vectors of the matrix U computed in a singular value decomposition (SVD) of the data matrix X. Here, we take the matrix X to be of dimension (NxM), where N is the number of rows and corresponds to the total number of time series points, and M is the number of columns, and is simply equal to the number of time series. The singular value decomposition of the matrix X is written as the product of three matrices:

$$X = UWV^T \tag{5.1}$$

or in index notation

$$X = \sum_{i=1}^{r} w_i\, u_i v_i^T \tag{5.2}$$

where r is the rank of X, u_i is the ith eigenvector of XX^T, v_i is the ith eigenvector of X^TX, and w_i is the ith singular value of X. A detailed derivation of these eigenvector relationships and the SVD itself can be found in Aki and Richards (1980) (also see Press *et al.*, 1986). The singular values w_i can be shown to be the positive square roots of the eigenvalues of the covariance matrices XX^T or X^TX (see Lanczos, 1961, for a derivation). The eigenvalues are always real and positive due to the positive definite nature of covariance matrices. In equation (5.2), the factor $u_i v_i^T$ is an NxM matrix of unitary rank which we call the ith eigenimage of X (e.g. Andrews and Hunt, 1977). Owing to the orthogonality of the eigenvectors, eigenimages form an orthogonal basis for the representation of X. As can be seen from the form of equation (5.2), the contribution to the construction of X of the eigenimage associated with a given singular value w_i is proportional to that singular value's magnitude. Since the singular values are always ordered in decreasing magnitude, the greatest contributions in the representation of X are contained in the first few eigenimages.

In our application, X represents the recorded time series from many different cycles of the primary waveform at the same location in space. Now suppose that all M time series are linearly independent, *i.e.*, no time series may be represented in terms of a linear combination of the other $M-1$ time series. In this case, X is of full rank M and all the singular values w_i are different from zero. Hence, the perfect reconstruction of X requires all eigenimages. On the other hand, in the case where all M time series are equal to within a scale factor, all images are linearly dependent; X is of rank one and may be perfectly represented by the first eigenimage $w_1 u_1 v_1^T$. In the general case, depending on the linear dependence which exists among the images, X may be reconstructed from only the first few eigenimages. In this case, the data may be considered to be composed of time series which show a high degree of series-to-series correlation. If only p ($p < r$) eigenimages are used to approximate X, a reconstruction error e is given by

$$\varepsilon = \|X_p - X\|^2$$

$$= (UW_pV^T - UWV^T)\,(UW_pV^T - UWV^T)^T$$

$$= \sum_{k=p+1}^{r} w_k^2 \tag{5.3}$$

where W_p is a diagonal matrix of singular values in which the singular values w_k in the range $p+1 \le k \le r$ have been set to zero.

We can now define band-pass X_{BP}, low-pass X_{LP}, and high-pass X_{HP} images in terms of the ranges of singular values used in the reconstruction. The band-passed image is reconstructed by rejecting highly correlated as well as highly uncorrelated images and is given by

$$X_{BP} = \sum_{i=p}^{q} w_i\, u_i v_i^T \qquad 1 < p \le q < r. \tag{5.4}$$

The summation for the low-pass image X_{LP} is from $i=1$ to $p-1$ and for the high-pass image X_{HP} is from $i=q+1$ to r. It may be simply shown that the fraction of energy which is contained in a reconstructed image X_{BP} is given by E, where

$$E = \sum_{i=p}^{q} (w_i)^2 \;\Big/\; \sum_{i=1}^{r} (w_i)^2 \tag{5.5}$$

The Karhunen-Loeve matrix of X is the matrix that contains the principal components and is denoted by K. K is an ($N \times M$) matrix, and is given by

$$K = XV. \tag{5.6}$$

This matrix multiplication represents a rotation of the input data X into the eigenvector frame ($v_1, v_2, \ldots v_M$). We note that the vector components of K (*i.e.*, k_1, k_2, ..., k_M) are mutually orthogonal. Using the singular value decomposition of X, we may write

$$K = UWV^TV \tag{5.7}$$

which, upon taking advantage of the identity $V^TV = I$ becomes

$$K = UW. \tag{5.8}$$

Recalling that ($v_1, v_2, \ldots v_M$) are the eigenvectors of X^TX, we now see that U is the signal matrix X after both projecting into the frame of the eigenvectors of the covariance matrix and normalization by division with the singular values.

6.0 Conclusions

We have described a research program to improve the utility of the TDEM method for UXO detection and imaging. The key component of our approach is to develop the forward and inverse solutions for the TDEM signals. This is a challenging problem due to the large conductivity contrasts characteristic of UXO.

A quantitative theory would provide the basis for interpreting the spatial-temporal complexity of the TDEM response, and would provide information that could be used to improve instrument design and the performance of target recognition algorithms based on neural nets. Finally, we suggested that the principal component transform provides a formal empirical basis for jointly interpreting responses from multiple sensor types, and for improving the signal to noise ratio of data from single sensor types.

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3-D Localization Using A Time-domain Electromagnetic System

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory has developed a unique time-domain electromagnetic system and data processing technique which can localize, in three-dimensions, the position of buried metallic objects. The measurement system uses conventional time-domain electromagnetic techniques on a scanning frame similar to a X-Y plotter. The system collects magnetic data over a large area above the buried object. The data are processed with an unique 'nearfield holographic' data processing method. This paper describes the data collection system, the nearfield holographic method, and experimental results.

INTRODUCTION

Increased interest in environmental clean-up and remediation of military bases and toxic dump sites have created the need for developing new techniques to 'see' into the ground. The potential danger involved in clean-up and remediation requires a more precise determination of buried materials' location, orientation, and size. To this end, the Johns Hopkins University Applied Physics Laboratory (JHU/APL) has developed a unique time-domain electromagnetic sensor and processing technique that can resolve and localize near-surface buried metallic objects.

The difficulty in localizing and characterizing underground objects with conventional electromagnetic (EM) sensor systems stems from the dissipative nature of the ground surrounding the buried object. Unlike air, which is transparent and almost lossless for EM wave propagation, the ground is conductive and generally inhomogeneous; the EM field is quickly attenuated with distance, and the EM wave satisfies a diffusion equation. Since dissipation increases with the frequency, to achieve penetration, an active electromagnetic sensor system should operate at low frequencies, with wavelengths in the earth typically hundreds to thousands of meters long. Long wavelengths would seem to indicate inherently poor spatial resolution for an active EM field-based sensor system. However, with a technique called nearfield holography, the spatial resolution is not theoretically limited by wavelength. This paper describes the nearfield holographic technique, the time-domain electromagnetic sensor system that collects the data, and experimental results.

NEARFIELD HOLOGRAPHIC TECHNIQUE

In its simplest form, the nearfield holographic technique is a combination of a straightforward EM measurement procedure and a unique treatment of the resulting EM data. The area where the target is buried is illuminated with an active transient time-domain EM source located on or above the ground. The field radiated from the source penetrates into the ground and induces eddy currents inside the target. These eddy currents act as a secondary source which re-radiates EM fields. The re-radiated EM fields from the target, or the time-rate-of-change of the secondary magnetic fields, are then measured at grid points in a horizontal plane at the surface of the ground in the vicinity of the buried target.

The time response of the magnetic fields measured at the surface is first Fast Fourier transformed (FFT) into the frequency domain, so that the secondary magnetic fields re-radiated from the target are obtained as a function of frequency. The magnetic field, after being transformed into the frequency domain, is a complex function having both magnitude and phase. At a particular frequency, the magnetic fields at the individual grid points in the detection plane form a spatial distribution of the measured magnetic field in that plane. The spatial variation of the magnetic field depends on the characteristics of the buried target and the distance from the target. This spatial distribution of the magnetic field at the detection plane is used to reconstruct the magnetic field distribution in the horizontal plane at various depths in the ground.

By examining the reconstructed magnetic field distributions in the horizontal planes at various depths,

the location of the target in both the horizontal and the vertical dimensions can then be determined.

The reconstruction of the magnetic field over a horizontal plane in the ground based on the magnetic field distribution in the detection plane is accomplished with the nearfield holography method, as illustrated in Fig. 1. The details of the method can be found in the References (Guo, 1994a; Guo, Ko and White, 1995).

TEM METHOD

Time-domain electromagnetic (TEM) techniques have been used for over 40 years in geophysical exploration. Figure 2 shows a simplified diagram of the TEM technique. After a current loop transmitter is placed in the vicinity of the buried target, a steady current is caused to flow in the transmitter loop for a sufficiently long time to allow turn-on transients in the ground to dissipate. The loop current is then quickly turned off. According to Faraday's Law, the rapid reduction in the transmitter's magnetic field induces an electromotive force (emf) in nearby conductors. This emf causes eddy currents to flow in the conductor with a characteristic decay time that depends on the conductivity, size, and shape of the conductor. The decay currents generate a secondary magnetic field, the time rate-of-change of which is measured by a receiver coil located above the ground.

SYSTEM DESCRIPTION

As depicted in Figure 3, the JHU/APL implementation of the TEM technique is composed of three major systems: a pneumatically-driven, mechanical scanning frame for the receiver coils; the transmitter and receiver electronics; and the data acquisition system.

The decaying magnetic field over the area above the target is measured by a linear array of 20-cm diameter coil receivers which is moved on an X-Y frame, much like an "X-Y plotter". The X-Y plotter frame is approximately 6m by 6m and is constructed of fiberglass and plastic. Nine receiver coils are located on a variable height coil cart. Both the coil cart and support frame are positioned using a pneumatically driven piston and claw system. An air compressor and pneumatic directional control valves are located about 33 m away from the frame, near the data acquisition system.

A simplified block diagram of the transmitter and receiver electronics are shown in Figure 4. The receiver coil electronics are located near the receiver coils and are connected to the data acquisition system via a 33 meter cable. The transmitter coil current is controlled by a 50% duty cycle, variable frequency quartz crystal oscillator operating at about 20 Hz. The oscillator's output is connected to a solid state switch near the transmitter coil. Current to the switch and transmitter coil is provided by a power supply located at the data acquisition system.

The transmitter coil is 1m by 1m square and is constructed of two turns of wire wound around two-inch diameter PVC tubing. The coil is shunted with a resistor to improve its turn-off time. As constructed, the transmitter coil and switch system can turn off about 12 A in about 450 ns (90% to 10%) with no ringing. Current in the transmitter coil is monitored via a series resistor connected on the ground side of the power supply. The voltage drop across the resistor is measured by the data acquisition system.

The toroidal receiver coils are 20 cm in diameter and have 100 turns of wire. Their frequency response (di/dt vs frequency) has been tested and found to be linear up to about 80 kHz. Each receiver coil is connected to its own amplifier via a short cable.

The receiver coil amplifiers, plus a battery operated power supply are housed in a water-resistant fiberglass enclosure. A receiver coil amplifier includes five components: input protection, analog switch, instrumentation amplifier, operational amplifier and current driver. The receiver coil input to the active circuitry is protected by a four diode/resistor array that clips any input signal at the positive or negative power supply voltage level. This protection is needed since the receiver coil can generate several hundred volts when it is near an active, full power transmitter coil. The analog switch is driven by a variable delay trigger that is synchronized with the transmitter signal. The purpose of the analog switch is to connect the receiver coils to the high gain amplifiers after the initial, high voltage turn-off transient from the transmitter coil has decayed in the receiver coil. A low-noise, instrumentation amplifier provides the first stage of amplification. The gain of the instrumentation amplifier was set at 100. The instrumentation amplifier is followed by a low-noise, operational amplifier configured as a two-pole, low pass active filter with a gain of 100 and a 3 db point of about 20 kHz. In order to drive the long data lines between the amplifier and the data acquisition system, a current driver was placed inside the feedback loop of the filter/amplifier. A 50 Ω decoupling resistor connects the amplifier to the data line.

Data acquisition is provided by an Analogic 12-channel, 16-bit analog-to-digital converter (ADC) subsystem installed in a Dynex 486, 33 MHz IBM compatible personal computer. The Analogic card has 4 Megabytes of onboard RAM that allows the ADC to collect about 6 seconds of uninterrupted data at 83 K

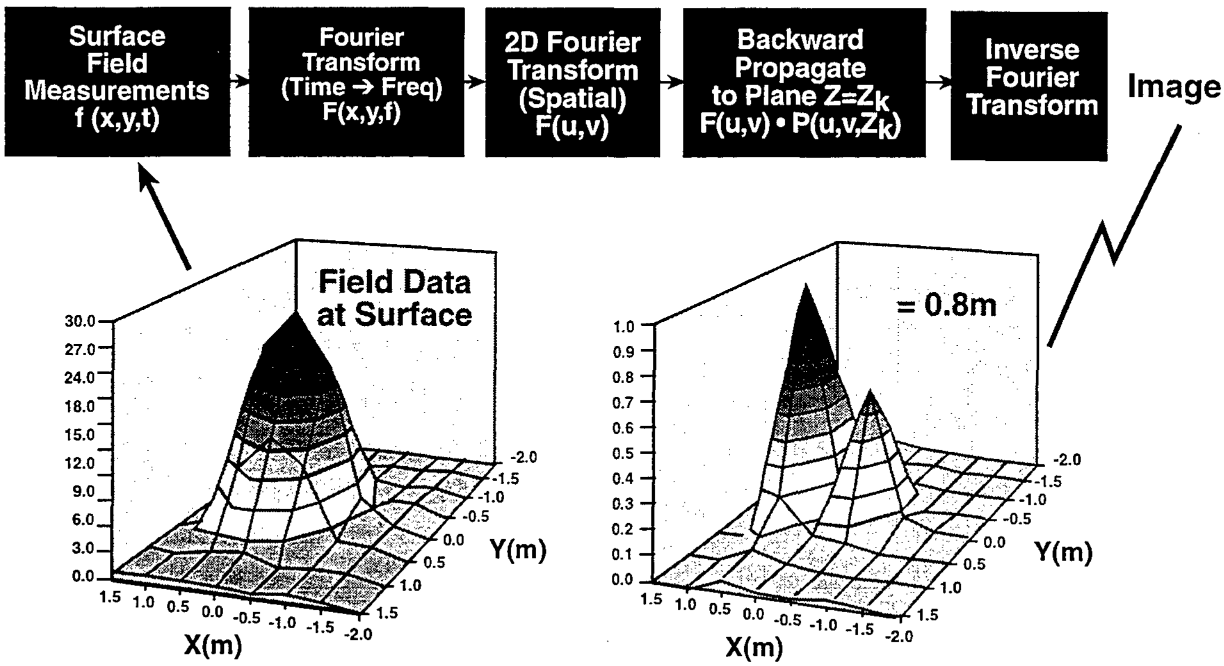

Figure 1. Nearfield Electromagnetic Holographic Method

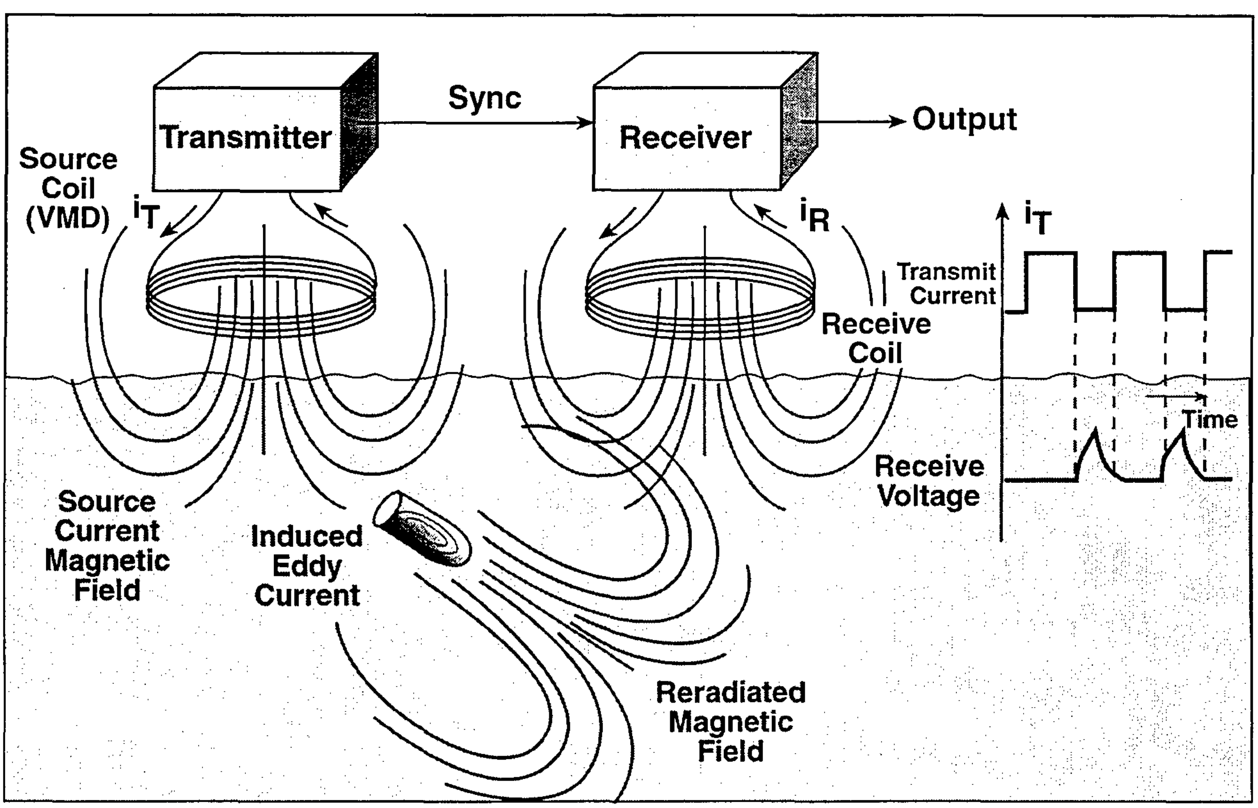

Figure 2. Time-domain Electromagnetic Measurement Technique

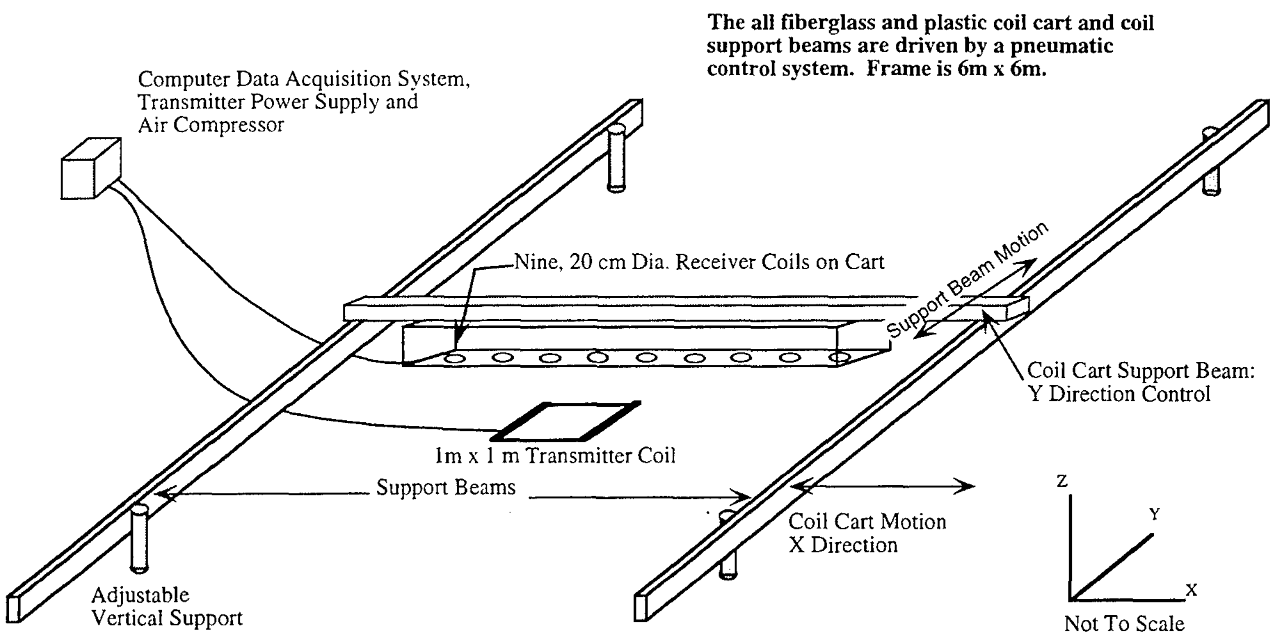

Figure 3 Time-domain Electromagnetic System and Scanning Frame

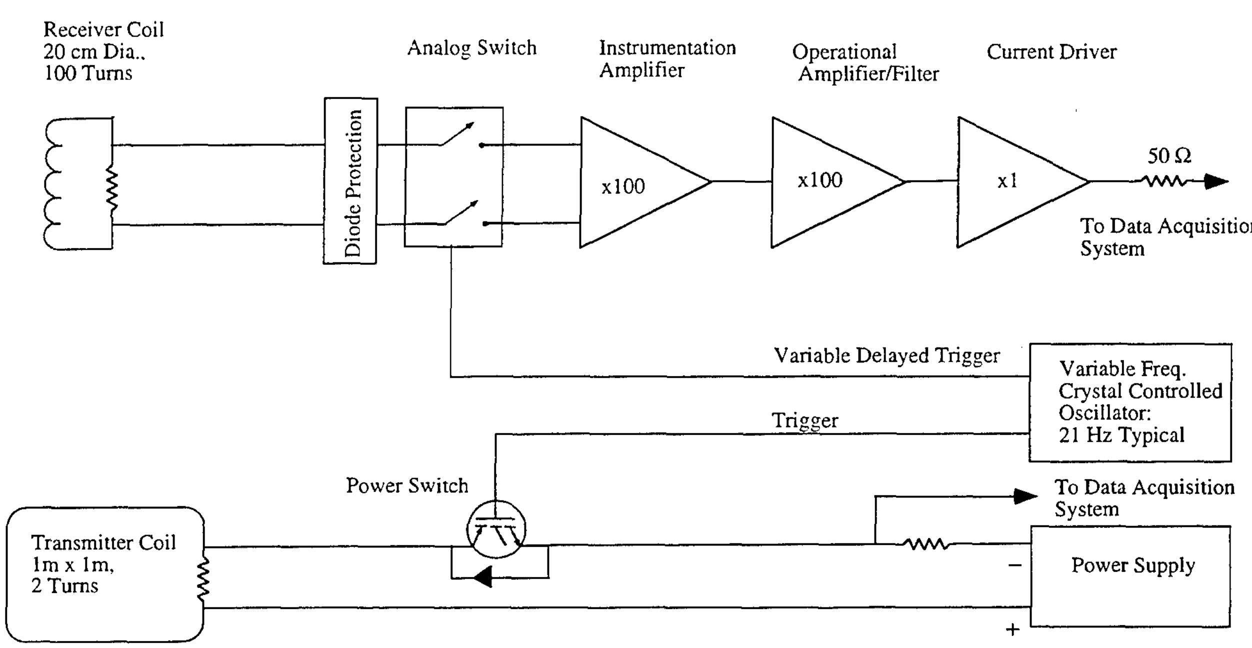

Figure 4. Simplified Diagram of Receiver and Transmitter Electronics

samples/s. The data are stored on a Bernoulli disk drive for post-test data processing.

SYSTEM OPERATION AND DATA PROCESSING

In a typical data collection scenario, the transmitter coil is placed over a suspected target. Centering of the transmitter coil over the target is not critical since the spatial magnetic field measurements will localize the target in a XYZ coordinate system referenced to the XY scanning frame. The first data collection station is at one end of the XY scanning frame. The data acquisition system collects about 6 seconds of data on the ADC RAM board. It then transfers the data to a Bernoulli disk. While data are being transferred to the disk, the scanning frame moves the receiver coils to the next data collection station. This sequence of operations is repeated until the scanning frame has swept the entire test area.

A preanalysis program separates the individual receiver channels from a pack binary format created by the data collection program. The data channels are synchronized with the transmitter pulses and averaged for about 100 transmitter pulse cycles. The resulting averaged time series is recorded as an ASCII text file.

The analysis program is written in the IDL programming language and performs the following steps. The spectrum of the magnetic field is obtained by applying an FFT to the individual data time series. At a chosen frequency, the nearfield electromagnetic holography method is applied to the data to reconstruct the spatial field distribution over the horizontal plane at a specified depth. For each reconstructed magnetic field distribution (RMFD) at a specified depth, the peak field is normalized to 1. By examining the RMFDs in the horizontal planes at various depths, the XYZ position of the target, relative to the scanning frame/receiver coils, can be determined. The location of the target is the point where the peak in the RMFD is in "focus" or most well defined. The results of the next section will make this idea of "focus" clearer.

TEST RESULTS

Two Buried Steel Pipes

A preliminary field test of the TEM holographic 3-D localization concept was conducted in August 1994 (Guo, 1994b). Spatial magnetic field data were collected using a Geonics PROTEM 57 TEM system. The PROTEM 57 system employed a 1m by 1m transmitter coil and a 60 cm diameter receiver coil. One of the tests used two steel pipes, 40 cm long and 15 cm in diameter with 3 mm walls. The pipes were buried vertically, 1 m apart and 40 cm deep (measured to top of pipe). The transmitter was laid on the ground above the targets. Because the measurements are very time intensive with a single coil system, they were taken on only one quadrant of a 3 m x 3 m grid. The center of the source and centerline of the targets were carefully aligned to ensure that the missing data could be obtained by symmetry.

Figure 5 shows plots of RMFDs at four depths. Plot A is the RMFD at the plane of the receiver coil. The two steel pipes project a very strong magnetic signal at the surface which appear as a large peak with two smaller peaks on top. Plot B, RMFD depth equal to 20 cm, shows the two smaller peaks separating indicating that the large peak in Plot A was in fact caused by two separate targets. The two targets are coming into "focus" as their true depth is approached. At an RMFD depth equal to 60 cm, plot C shows the two peaks clearly separated. RMFDs at depths between 40 cm and 70 cm are almost identical, with well defined peaks. This is the region occupied by the pipes. However, as shown in plot D, at a RMFD depth equal to 100 cm, the peaks have started to recombine, and become less distinct. This depth is beyond the bottom of the pipes, the RMFD becomes "defocused."

The ability of the holographic technique to resolve horizontal position is also shown in Figure 5. The two peaks of the RMFD at 60 cm depth are 1 m apart. This inferred separation distance matches exactly the 1 m separation of the buried pipes.

Two Aluminum Disks

A test of the scanning frame TEM system was conducted on 30 January 1996 using the JHU/APL designed system. The targets were two small aluminum (Al: 6061-T6) disks, 12.7 cm in diameter and 5.7 cm thick. To facilitate different testing configurations, the disks were not buried but were placed on the surface, in the center of the transmitter coil. Preliminary concept testing in 1994 (Guo, 1994b) had shown only slight differences between data taken with targets in the air and targets buried in the ground. For the test reported here, the disks were separated by 51 cm and the receiver coil array was raised to 41 cm above the center of the disks. To speed up the data collection, only two thirds of the test area was scanned as the magnetic field was assumed to be symmetric about the centerline between the two disks. The missing data points in the unscanned area were filled in by the data points in the scanned area.

Figure 6 shows plots of RMFDs at four depths. Plot A is the RMFD at the plane of the receiver coils. Because the two Al disks project a weak magnetic signal, one cannot be certain as to what kind of target is being scanned. At a RMFD depth equal to 20 cm, plot B shows two peaks beginning to appear. At a

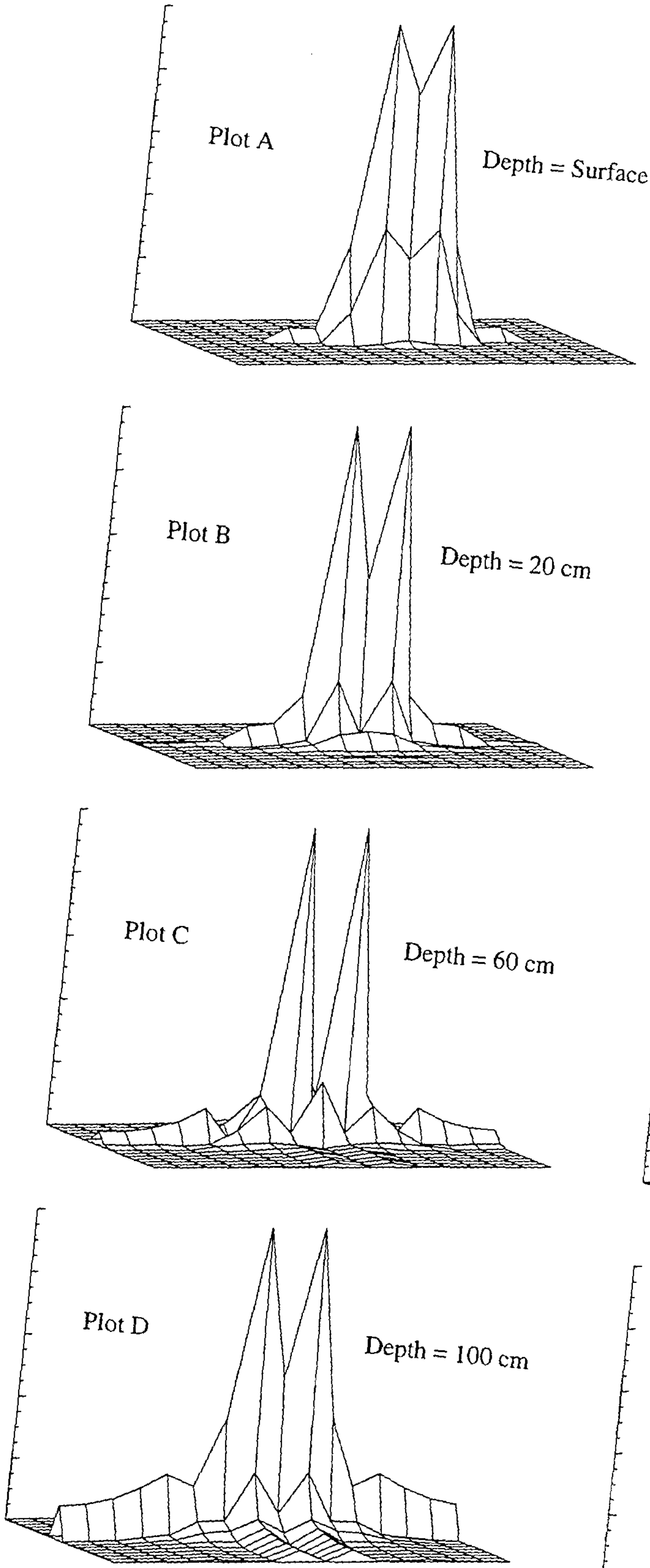

Figure 5. Reconstructed magnetic field distribution plots for two steel pipes at 40 cm depth.

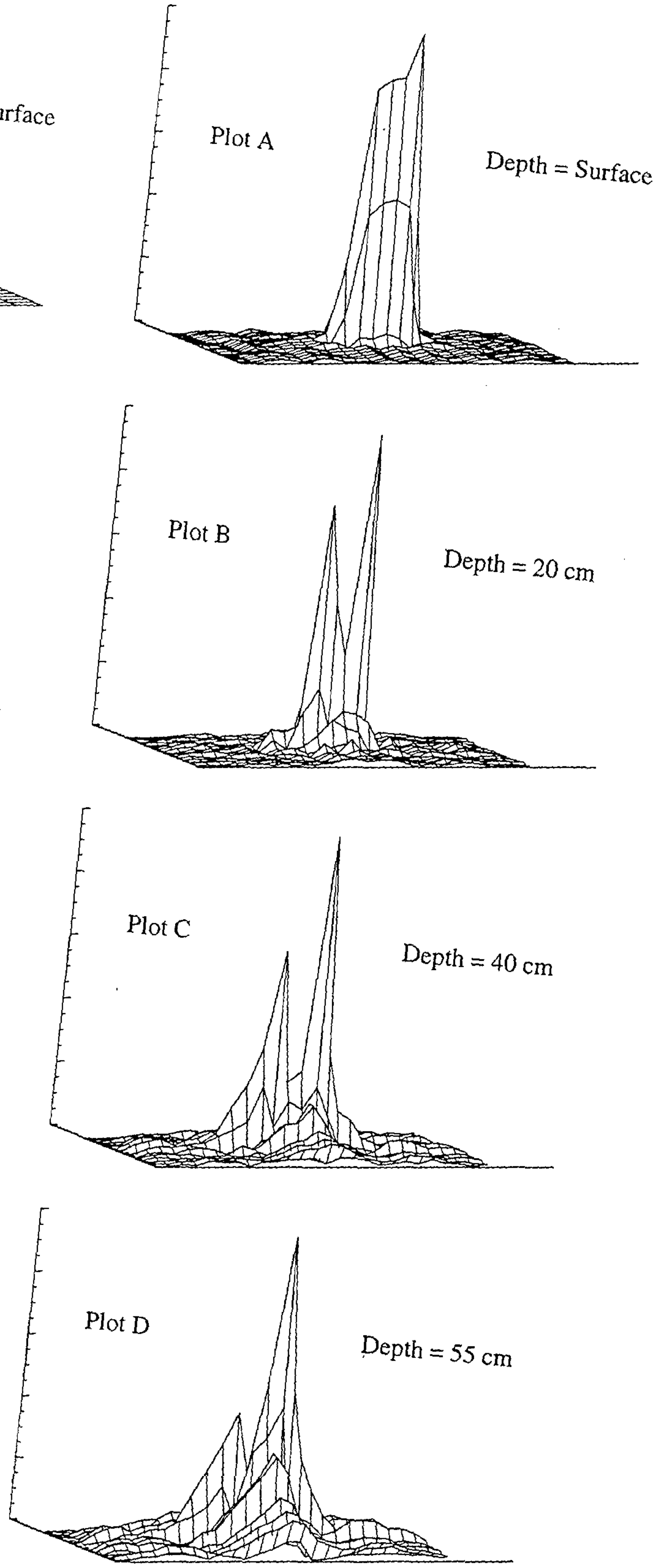

Figure 6. Reconstructed mangetic field distribution plots for two Al disks at 41 cm depth.

RMFD depth equal to 40 cm (approximate target depth), plot C clearly shows the two peaks separated. In plot D, RMFD with a depth equal to 55 cm, the peaks start to recombine, and become more diffuse, and out of focus.

The two peaks in Figure 6 indicate that the horizontal separation of the Al targets is about 60 cm (three grid points). The real separation distance was 51 cm.

DISCUSSION

The receiver coil signal is proportional to the sixth power of the range to the target. Small range changes cause large changes in received signal strength. Figure 6 shows that the RMFD peaks are not symmetric in amplitude. This is because the receiver coil array was not precisely aligned with the targets as the scanning frame moved across the test area. In this case, as the receiver coil array was scanned over the two targets, the receiver coils were closer to the 'right' target (as shown in Figure 6) than to the 'left' target. Hence, the signal was stronger when the receiver coils were over the 'right' target. However, signal amplitude is not the important parameter in the TEM holographic technique. It is the spatial properties that are important.

CONCLUSIONS

This report described a TEM system to measure the spatial magnetic field properties of buried metal objects. The ability of the nearfield holographic technique to localize and discern multiple buried objects in three dimensions (3D) was also demonstrated using the spatial TEM data. The positional resolution for buried metal objects in the XY plane is on the order of the receiver coil measurement spacing while the resolution in the Z direction depends on the data scanning window, receiver coil spacing as well as the dynamic range of the sensor system.

The scanning frame, electronic system, and data acquisition system were designed as research tools to explore the uses and quantify the performance of the TEM nearfield holographic technique. In future system designs, the electronics and scanning methods can be optimized for specific target objects and environments.

ACKNOWLEDGMENTS

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TESTING OF SURFACE UNEXPLODED ORDNANCE DETECTION VIA AN ACTIVE/PASSIVE MULTISPECTRAL LINE SCANNER SYSTEM

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ABSTRACT

This paper describes the use of a helicopter-mounted multispectral line scanner system as a tool for detecting unexploded ordnance at the terrain surface. The system was originally designed for remote minefield detection. This adaptation will help aid in the cleanup of Department of Defense (DoD) sites with unexploded ordnance (UXO) contamination. Existing technologies for detection and remediation of UXO are expensive, dangerous to personnel, labor intensive, and technologically inefficient. The use of airborne remote detection minimizes the risk to personnel during the environmental assessment and analysis of the site. The system, called the REmote MInefield Detection System (REMIDS), consists of an active/passive multispectral line scanner, real-time processing and display equipment, and navigational equipment. The scanner collects three channels of optically aligned image data consisting of two active laser channels, one polarized reflectance and the other total reflectance, and one passive thermal infrared channel. The real-time processing and display system is based on parallel processor technology. The system can be flown at various altitudes and forward speeds to characterize sites for the presence of surface UXO. The system also incorporates onboard recording and the insertion of differential Global Positioning System (GPS) coordinates. GPS coordinate information will allow contaminated areas to be added into a Geographical Information System (GIS). The detection is based on the remote identification of surface anomalies and materials which indicate the presence of surface UXO contamination. The results presented are from the test flights performed at Fort Rucker, Alabama on UXO material sent from Jefferson Proving Ground, Indiana and Yuma Proving Ground, Arizona. The test flights are funded by the Environmental Security Technology Certification Program (ESTCP) and managed through the Army Environmental Center (AEC). The system shows promise for a secondary use for surface UXO detection.

INTRODUCTION

There is increasing need for dual-use or multi-use technology due to current and anticipated DoD budget reductions. Through funding from ESTCP, REMIDS is now being evaluated for a secondary use of surface UXO detection. The initial test flights have been performed at Ft. Rucker, Alabama using the UXO material sent from Jefferson Proving Ground, Indiana and Yuma Proving Ground, Arizona. Test flights will be performed at Jefferson Proving Ground, Indiana and Yuma Proving Ground, Arizona later during the fiscal year. The U.S. Army Aviation Technical Test Center (ATTC), Ft. Rucker, Alabama, provided aircraft support. The Waterways Experiment Station (WES) personnel operated the airborne scanner and processed the data collected from the test flights.

BACKGROUND

The airborne data collection system consists of an active/passive line scanner, real-time processing and display equipment, and navigational equipment and is described in detail elsewhere (Ballard 1992). The scanner collects three channels of optically aligned image data consisting of two active laser channels (one polarized reflectance and the other total reflectance) and one passive thermal infrared channel. The real-time processing and display system is based on a massively parallel processor. The system has a scan rate of 350 scans per second with 710 data pixels per scan. The system can be flown at

different altitudes. Low altitude (130 ft.) flights are flown with a forward speed of 30 knots to characterize the site for the presence of surface UXO. This allows for the surface scan resolution to be nominally 1.9 x 1.9 in. Typical coverage for a single pass during one hour of flight is 300 acres. Medium altitude (200 ft.) flights are flown at a forward speed of 52 knots. This altitude and forward speed gives a nominal surface scan resolution of 3.0 x 3.0 in. Typical coverage for a single pass during one hour of flight is 900 acres. High altitude (400 ft.) flights are flown at a forward speed of 104 knots. This altitude and forward speed gives a nominal surface scan resolution of 6.0 x 6.0 in. Typical coverage for a single pass during one hour of flight is 3600 acres. The detection is based on the remote identification of surface anomalies and materials which indicate the presence of surface UXO contamination. A cut-away diagram of the scanner is shown in Figure 1.

SITE PREPARATION

Staging Area

The calibration site and the test site were setup at the Highfalls staging area of Ft. Rucker, Alabama. The vegetation coverage was grass and broad leaf weeds with an average height of 2.0 cm. The soil particle size characteristics are given in Figure 2. The soil plasticity is none and the soil moisture content ranged from 7.0% to 10.2% during the test flights.

Calibration Site

The layout of the calibration site is shown in Figure 3. The calibration site consisted of water containers, roofing material, UXO material, reflectance standards, resolution targets, and black and white panels. The roofing material, reflectance standards, and resolution targets were used to calibrate the active laser sensors. The water containers, and black and white panels were used to calibrate the passive infrared sensor. The UXO material was used to define the classification of the UXO material in the test site. Temperatures of the water containers, black and white panels, and UXO materials were collected during the day of the test flights. The weather data (temperature, relative humidity, wind direction, and precipitation) were also collected throughout the test flight day.

Test Site

The survey of the test site is shown in Figure 4. The test site contained UXO material and other man-made material. The UXO material consisted of whole and fragments of 155mm, 152mm, 106mm, and 105mm projectiles; 81mm and 60mm mortars; and 40mm grenades. The man-made materials consisted of aluminum cans, electrical cable, a 55 gal drum, glass and plastic containers, and expended small arms casings. The test site also contained roofing material from previous construction at the Highfalls staging area. The non-UXO materials were placed in the test site as representatives of items that may cause false positives. A false positive is the classification of a non-ordnance item as an ordnance item.

DATA COLLECTION

The samples collected by the system are three digital channels. The three channels are polarization, reflectance, and thermal. The system was flown at an altitude of 130 ft. with a forward speed of 30 knots to collect the samples. This allowed for the surface scan resolution to be nominally 1.9 x 1.9 in. This resolution allowed for detection of smaller UXO material. The resolution is the same for both the active and passive channels.

The test flights were flown on 09 March 1996, 11 March 1996, and 12 March 1996. The flight paths were flown with headings of 0, 90, 135, 180, 270, and 315 degrees over the calibration and test sites. This allowed for different orientations of the ordnance material with respect to the scanner for shape filter testing.

The GPS data collected during the test flights was real-time corrected differential GPS. The GPS equipment (Trimble 1992) used for the survey is independent of the scanner system. The synchronization of the information between the GPS system and the scanner system was integrated together via time stamps.

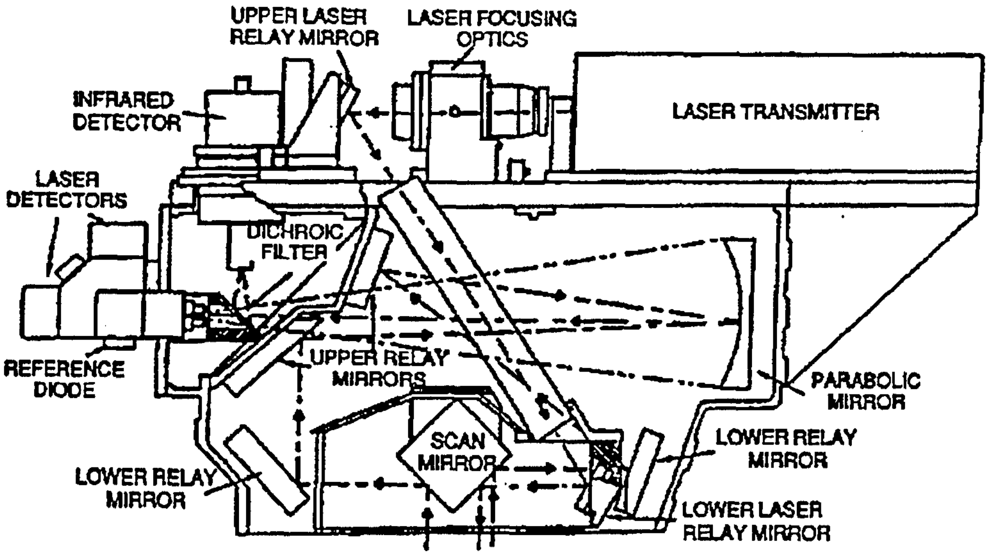

Figure 1. Scanner Physical and Optical Layout

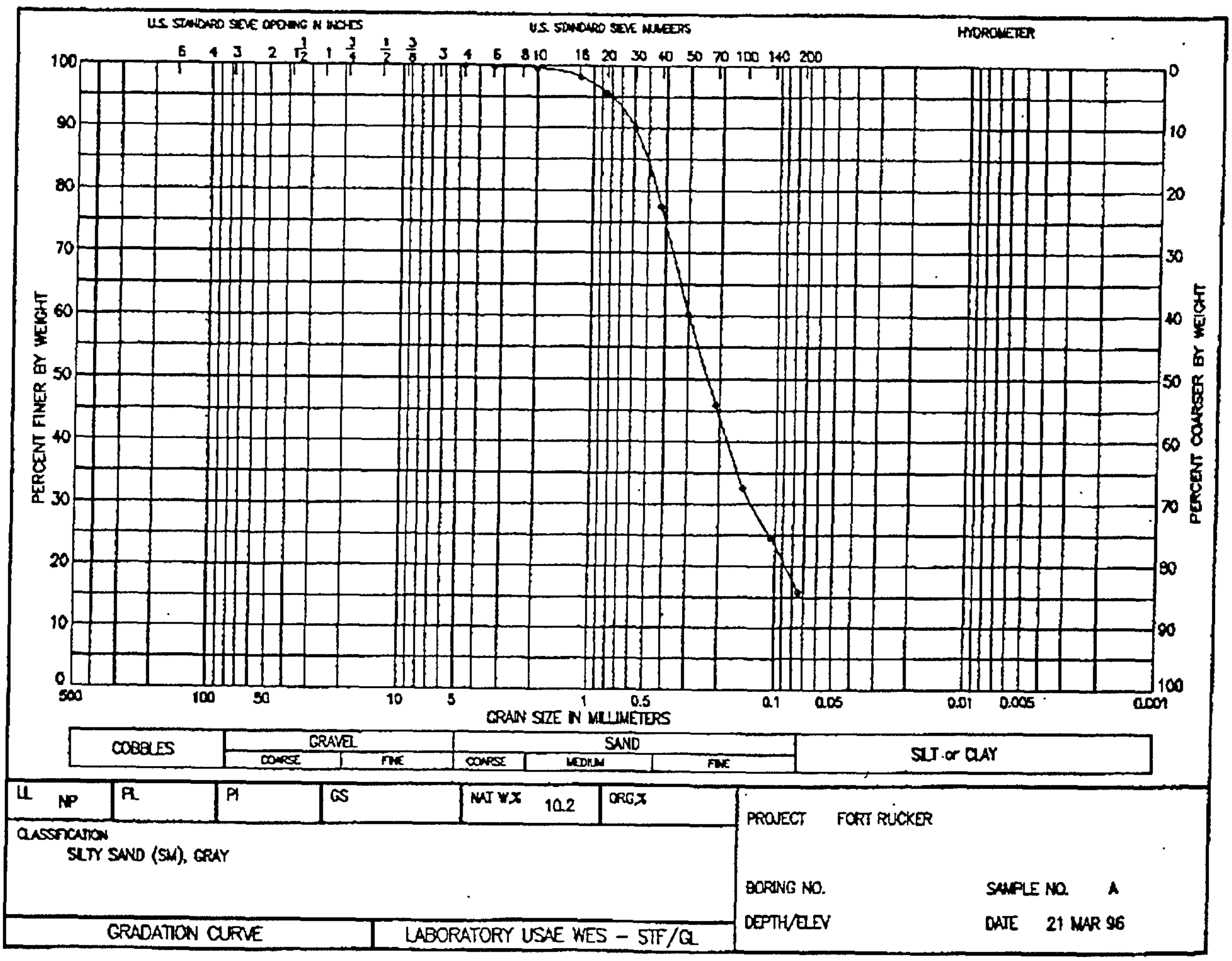

Figure 2. Fort Rucker Soil Sample

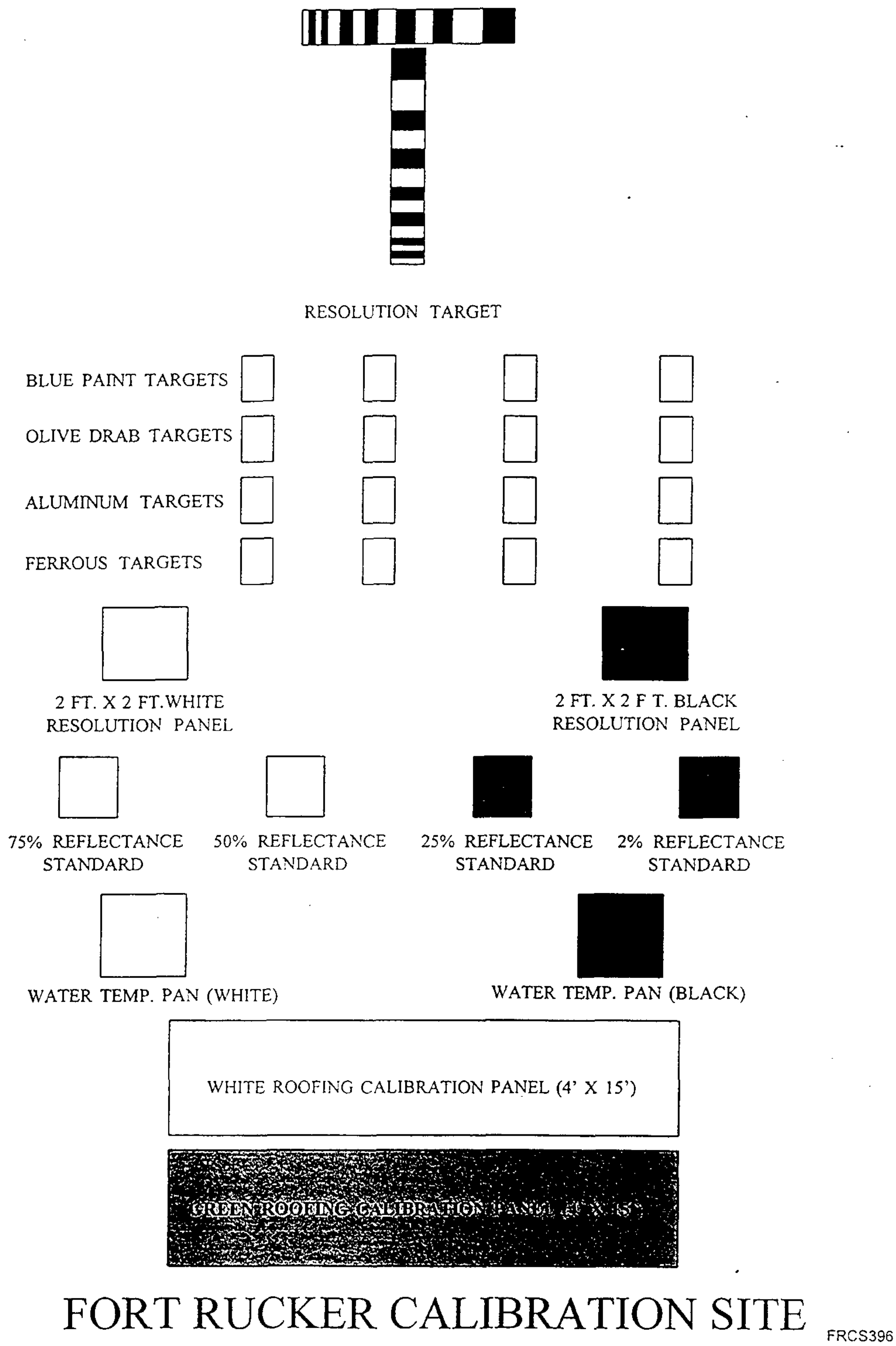

Figure 3. Calibration Site Layout

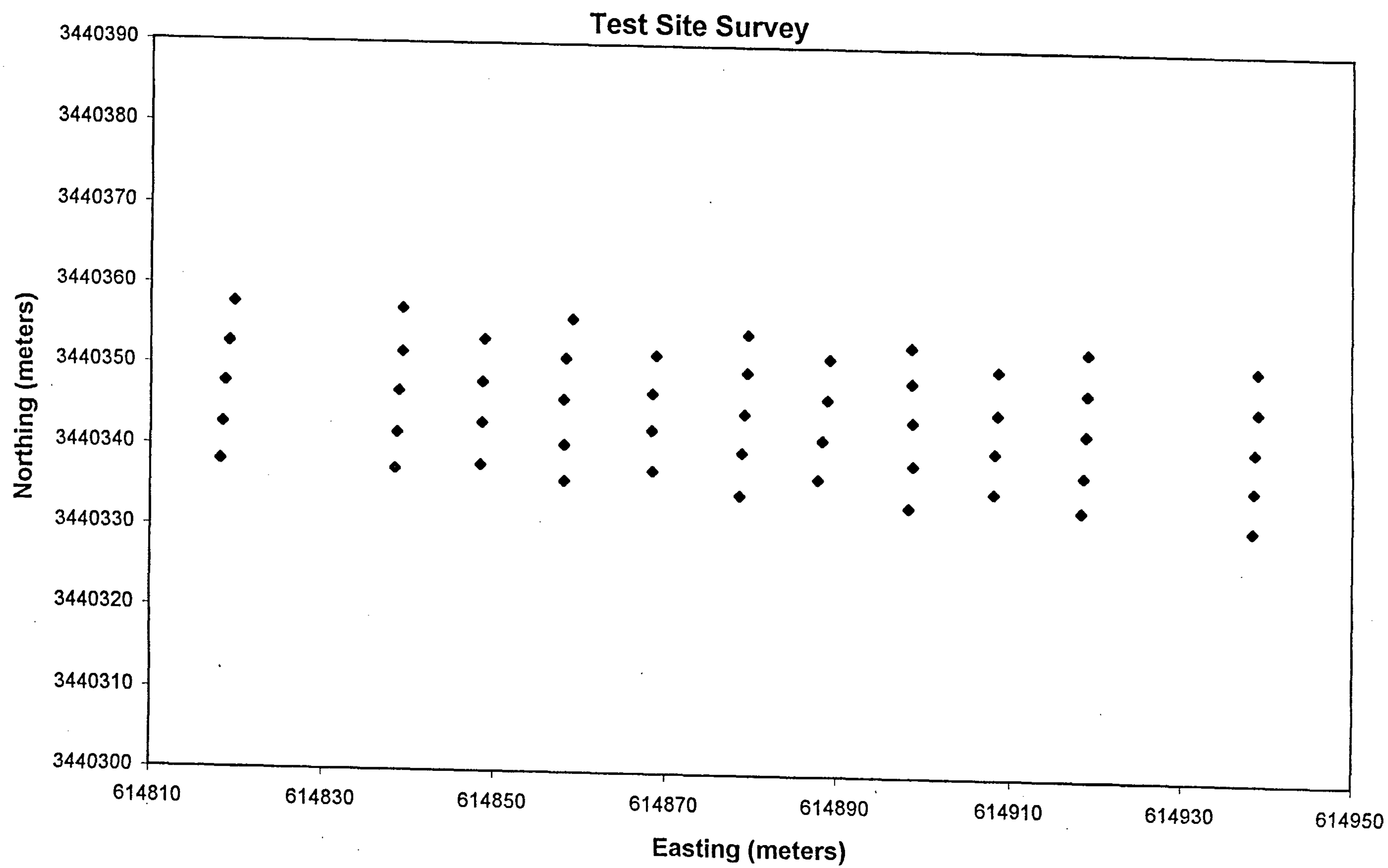

Figure 4. Survey of Test Site

RESULTS

Imagery

A picture of ordnance materials used in the test site with images of the three channels collected is presented in Figure 5. The top image is the polarization image. The middel image is the reflectance image. The bottom image is the thermal image. The images were taken from the 10:55 am test flight. The air temperature at this time was 10 degrees C and the soil temperature was 14 degrees C.

Data Fusion

The three channels were fused together as shown in the decision space graph given in Figure 6. The 3D histogram represent the background and UXO material data points. The polarization, reflectance, and thermal parameters are represented in the axes. The solid spheroid represents the threshold detection space for aluminum.

Global Positioning System

The RMS error between the test site survey points and the test flight target points was less than 3.0 meters for test flights flown with wind velocities less than 10 knots. The RMS error for test flights flown with wind speeds greater than 20 knots was less than 4.0 meters. The lack of yaw and pitch compensation was the main factor for the increase RMS error.

CONCLUSIONS

REMIDS has demonstrated the ability to detect surface UXO materials. This system has also shown the ability to detect a wide range of man made objects. Thus, work is needed in algorithm development to minimize false alarms and to target only those anomalies that are surface UXO related. REMIDS technology is currently being enhanced by Raytheon Corporation as part of the Airborne Standoff Minefield Detection Program. Their effort will produce a downsized higher resolution active/passive system capable of operating from an unmanned aircraft. Any algorithm development for other uses of REMIDS would aid in the quick adaptation of the Raytheon system when its development stage is completed.

The use of an inertial navigation system, to track the helicopter orientation, would aid in the reduction of GPS errors due to yaw and pitch.

The need for accurate flight path control has also been shown. The elimination of overlapping flight paths and uncovered areas would greatly increase the efficiency and reliability of manned and/or unmanned airborne platforms.

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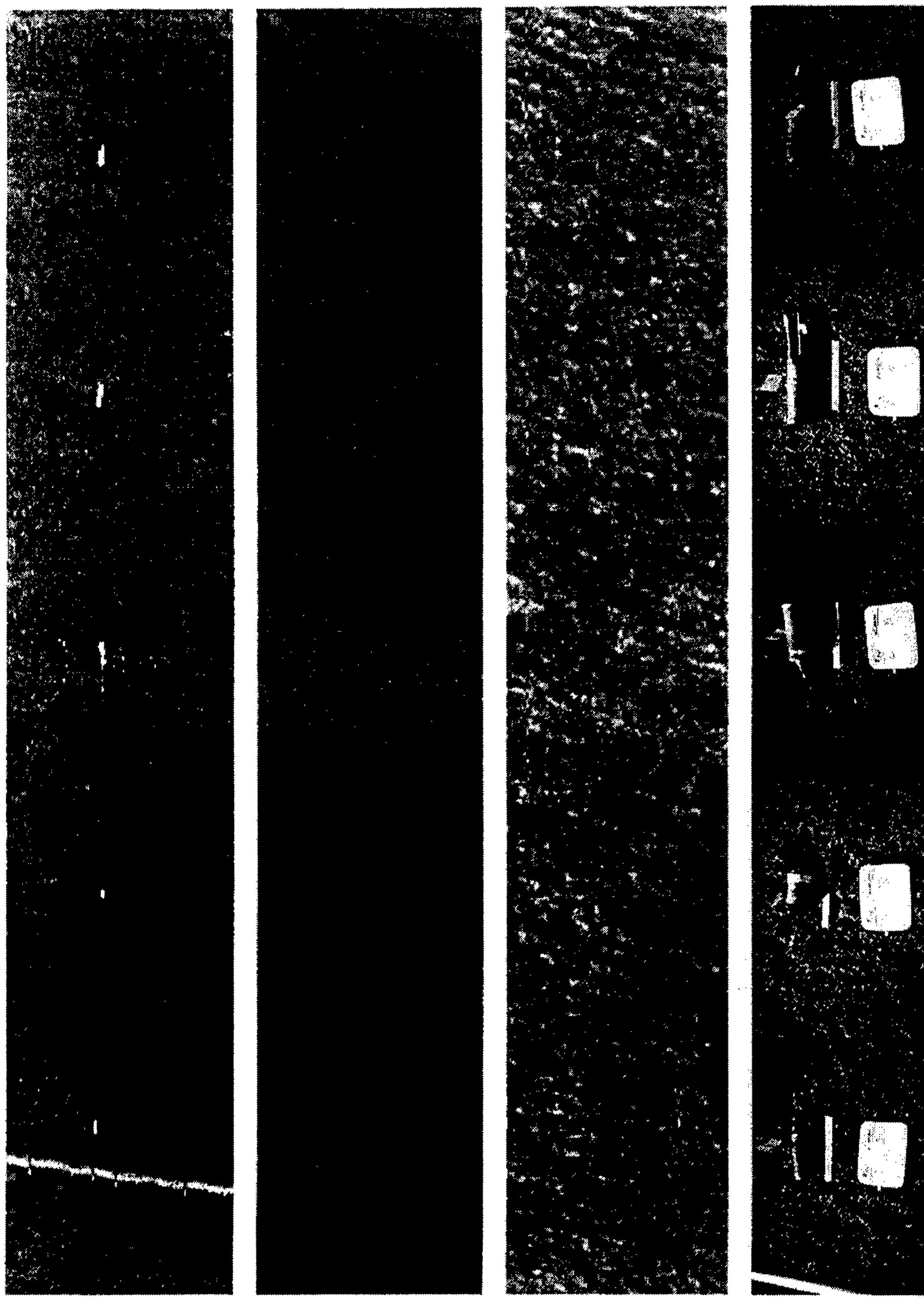
Trimble Navigation, Ltd. (1992) "System Operating Manuals." Sunnyvale, CA: Trimble Navigation.

ACKNOWLEDGEMENTS

Permission was granted by the Chief of Engineers to publish this information.



Polarization Reflectance Thermal Pictures

Figure 5. Imagery

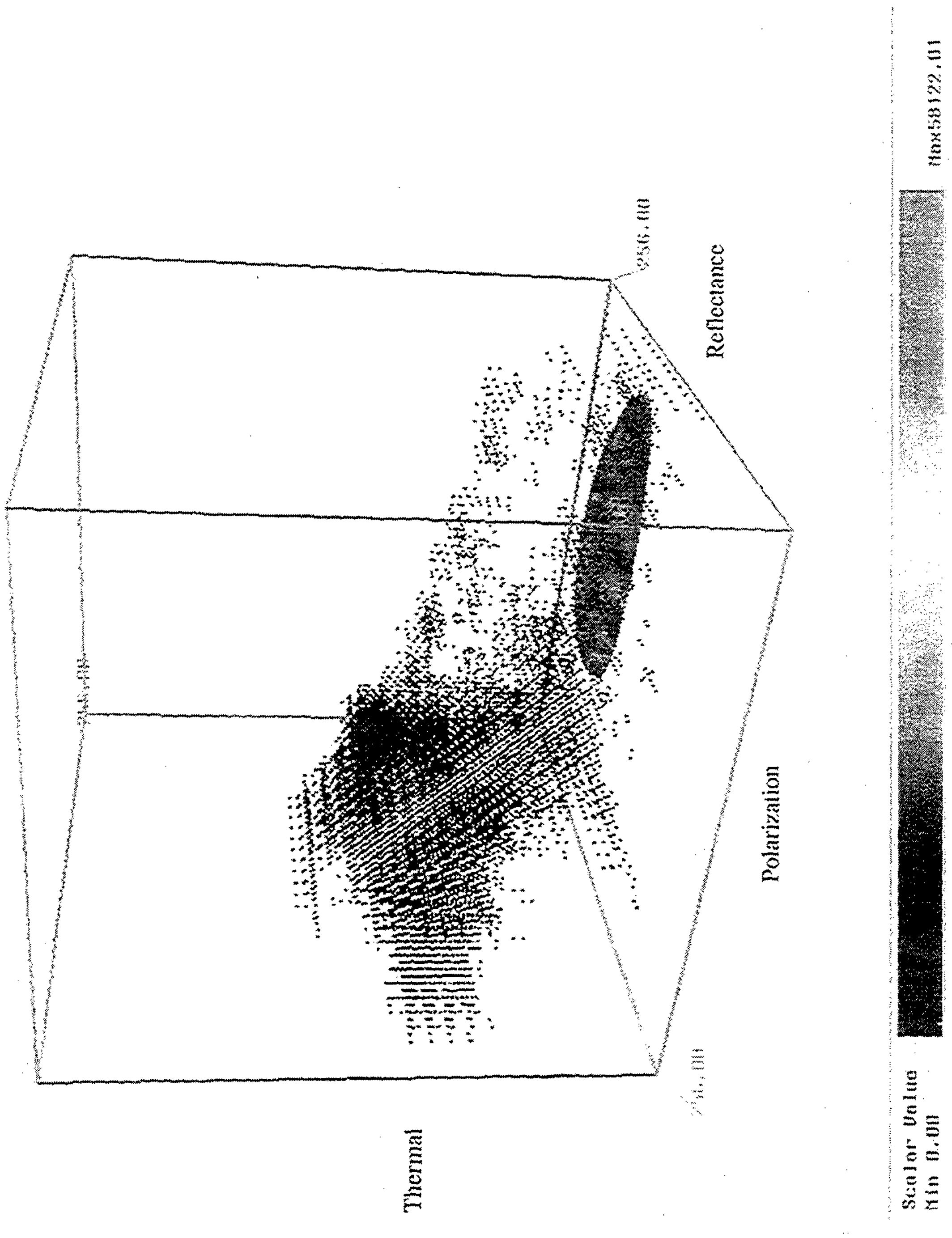


Figure 6. Decision Space Graph

UXO DETECTION BY A COMBINED RADAR AND ELECTRO-MAGNETIC SENSOR SYSTEM

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ABSTRACT

Advanced Technology Live Site Demonstrations at the Yuma Proving Grounds (YPG) in Arizona and at McChord AFB in Washington State have shown that a mixed technology, vehicle towed multi-sensor array configuration can effectively cover large UXO contaminated areas in a timely manner. Electro-Magnetic sensor, Ground Penetrating Radar and Differential Global Positioning System technologies have been integrated to form a system that can reliably detect and locate UXO. Unique interactive sensor control and data collection, as well as real-time data processing and off-line data fusion algorithms have been developed that greatly enhance overall system efficiency. However, demonstration results to date indicate that the evaluation of sensor discrimination performance, especially GPR data analysis, must continue -- perhaps over smaller, well defined target areas and with more relaxed time constraints.

OBJECTIVES

Our short-term objectives at both Yuma and McChord were: (a) to demonstrate that a small crew, operating with high performance sensors, could provide fast and economical coverage of the required acreage in the time allotted, (b) that the system demonstrated would operate reliably over a wide range of terrain and weather extremes, (c) to perform on-site data processing on a daily basis to reduce the post processing effort and to meet data reporting time requirements. Our long-term objective was to record sensor data that we could compare with the "known" target list so that we could complete the target recognition phase of our 3-year IR&D program on UXO detection.

At Yuma, we were only able to meet objectives (a) and (b), while at McChord we were able to achieve all of our short-term objectives by conducting on-site processing of collected data on a daily basis The "known" target lists were not received in time for inclusion in this paper, but we will be using them to test recognition algorithms over the next year.

DEMONSTRATION SITES

Weather and terrain conditions at the two sites varied to the extreme. Temperatures at Yuma in July ranged from 130 degrees F during the day to 90 degrees F at night. At McChord in November, on dry sunny days the morning temperatures were in the teens and would climb to the fifties -- on rainy days it would be wet to very wet and in the 40's. The terrain at both sites ranged from relatively clear (few obstacles) to completely unnavigable. Yuma had its gulches and gullies while McChord had random outcroppings of trees and piles of debris. The marginally cleared wooded areas at McChord were a challenge, yet our vehicle-towed sensor array did remarkably well in negotiating the many tree stumps, fallen logs, and bushes encountered.

OPERATIONAL TEAM

The operational team at Yuma included four technologists and two EOD technicians. A crew of four were in the test area at any given time -- a driver, two sensor operators and a grid navigator. During collection operations at McChord, the on-site team consisted of three technologists and one EOD technician. A crew of three manned the sensor vehicle while it was on the grid: a driver, a navigator and an equipment/sensor operator. The fourth team member remained at the grid staging area and processed collected sensor data.

SYSTEM DESCRIPTION

The system demonstrated at both Yuma and McChord was a mixed multi-sensor platform that included the METRATEK Model 200 radar in its Synthetic Aperture Radar / Ground Penetrating Radar (SAR/GPR) configuration, three Electro-Magnetic Sensors (EMS) , and a Real-Time Kinematic Differential Global Positioning System (RTKDGPS) for navigation and location of UXO targets.

The SAR/GPR system operated with a step-chirp waveform driving three pairs of antennas flush-mounted on a sled made from a strong sheet of plastic. The three EMS sensors were mounted behind the GPR antenna sled on their own wheels and attached by rubber couplings to a fiber glass

towing frame. The RTKDGPS rover station antenna was mounted on the towing vehicle.

A four-wheel drive Chevrolet Suburban with raised clearance and ruggedized off-road tires was used to tow the GPR and EMS sensor arrays. The vehicle carried a generator on the front bumper and was heavily air-conditioned; this allowed the crew to operate continuously without losing time due to needing heat breaks. The GPR and EMS system electronics as well as the RTKDGPS rover receiver were housed in rear seat area of the vehicle, facing forward. The GPR, EMS and RTKDGPS were controlled from three real-time displays in the vehicle, and a TV display permitted the two operators to view the sensor sled. The vehicle and the towed array are shown in Figure 1.

SAR / GPR Radar System

The METRATEK Model 200 GPR system is a coherent stepped-frequency Synthetic Aperture Radar (SAR) that can be configured to meet virtually any application that requires precise SAR measurement and imaging. It has an excellent track record as a highly accurate radar cross section (RCS) measuring instrument. All waveform parameters are computer controlled and can be quickly changed by the operator to match the conditions at hand. At Yuma and McChord the Model 200 was configured as a GPR and operated in the 150 MHz-2 GHz frequency range.

The GPR transmitter and receiver parameters were adjusted to compensate for the ground conditions. The radar transceiver is time-multiplexed between three antenna arrays, each consisting of a transmit and receive antenna. The antennas are kept in close contact with the ground by mounting them with Velcro on a sled made of tough but flexible plastic sheeting. The sheeting is inexpensive and is intended to be replaced when worn by rough surfaces. The sheeting was replaced 5 times at Yuma because of the harsh, abrasive gravel surface.

The received SAR data is processed to provide a high resolution down range picture of the radar reflectivity. This downrange profile is displayed to the operator in real time and the raw radar data are recorded on removable hard disks for off-line processing.

An encoder driven by a wheel on the side of the four wheel drive towing vehicle is used to trigger the radar. The real-time radar display shows target strength in color, depth vertically, and distance along the ground horizontally. All three radar outputs are displayed simultaneously from top to bottom across the display. Figure 2 shows the Model 200 GPR installation and display.

Electromagnetic Sensor System

An array of three Geonics EM61 time domain metal detectors was mounted behind the GPR antenna sled. The EM61 is capable of detecting both ferrous and non-ferrous metal objects. This sensor operates by generating a pulsed magnetic field, which in turn induces eddy currents in any nearby metal objects. The decay of the induced eddy currents is measured by the sensor coils.

The EMS system was operated via a laptop computer that controlled the data collection, provided a real-time display, and recorded the three EMS channels to disk. The laptop was mounted on a swing-arm that positioned it in front of the right-hand console shown in Figure 2.

Sensor Sled and Trailer

The sensor arrays are mounted on a lightweight assembly consisting of a fiberglass trailer frame and the GPR sheet/sled. Both the sled and trailer are made of readily available, inexpensive materials that can be replaced or modified to match conditions at each site. The sensor sled/trailer is 4.5 meters wide and covers a swath of 5 meters when terrain permits. The width can be reduced to 3 meters (two pairs of sensors) for access to wooded areas and more difficult terrain. When the terrain is too rough for the vehicle, the sensors can be dismounted and used in a man-portable configuration; this was done at McChord, although there was little time remaining to perform as thorough a search as we would have liked.

RTKDGPS Navigation System

The Real-Time Kinematic Differential GPS (RTKDGPS) was used to provide sub-meter positional accuracy for vehicle navigation, timing and target location data. The system consisted of two Trimble 4000SSE Surveyor DGPS systems -- a base station placed over a known reference point and a rover station mounted inside the sensor towing vehicle. Communications between the base station and rover was via 900 MHZ TrimTalk radio link.

A real-time GPS data display mounted on the dash board of the towing vehicle to assist the driver in navigating the grid. The data was displayed on an overlay of the grid that was being worked at the time. Positioning and timing data were differentially corrected, recorded and displayed in real time in the vehicle at one second intervals. The 3-second latency for the differential corrections made it necessary to post-process the sensor data to align the sensor data with the GPS tracks.

Data Collection System

The GPR data are collected and processed using a 486/65 MHZ computer. The output samples of the coherent radar returns are processed to provide a real-time operator display of all three antenna pairs, and the data are written to removable disk. The detection function is performed in real time, while off-line processing is used to revisit targets of interest and to provide additional discrimination. All system software from interactive system control and data collection to real-time display and off-line SAR image processing has been developed in-house by METRATEK.

Raw data from the EMS sensors is sent through a serial multi-port adapter interface to a laptop computer running in the WINDOWS environment. The data from the EM61 sensors is collected, processed and displayed in real time using METRATEK-developed LABVIEW software. This software provides an interactive environment through which the operator can control and monitor the collection of EMS survey data and set processing parameters and detection thresholds while data are being collected. The EMS data are stored on removable disks and can be re-processed off-line to review and/or confirm real-time results.

Raw data from the GPS system is processed by a laptop computer running GPSlog software under WINDOWS. The processed data is presented in a real-time (3 second latency) "bread crumb" type track display to assist the vehicle driver in maintaining proper course and heading. The GPSlog software also converts the WGS-84 latitude/longitude data in real time to UTM coordinates and stores it on 3.5" floppy disks. A typical plot of one day's runs at Yuma is shown in Figure 4. The spaces between the GPS tracks are due to the need to avoid obstacles. (The ground rules of the tests prohibited the movement of obstacles by the test crews.)

On-Site Data Processing

At Yuma, an insulated air-conditioned van was shipped from METRATEK to provide a rest area for the crew and to house data processing operations. At McChord, a large rental truck was adequate for this purpose. It was located at the grid staging area. Power was provided by an external generator. One team member remained in the truck and processed collected GPR, EMS and GPS data on a daily basis. On-site processing generated daily grid coverage plots and pin-pointed areas requiring revisits or additional coverage.

OPERATIONAL SCENARIO - YUMA PG

The demonstration area at Yuma Proving Grounds was made up of two sites; the DRA Site (Steel Circle) and the Live Site (HULK3). The DRA site consisted of 39 acres of relatively flat terrain, interspersed with several washes running laterally through the area. There was relatively little metallic surface debris at the site, but it was covered with a species of sticker bushes with 2-inch long needle-like thorns -- these gradually deflated the tires on the sensor sled the first day. This did not substantially affect sensor speed or performance, but the inner tubes were replace with solid rubber ones which were not susceptible to the needles. The site was staked out in 252 grid squares, each 25 x 25 meters. Two "known" targets were located on the DRA site, however we were never able to detect and/or verify their exact position. This proved to be detrimental to our overall effort as we were not able to perform a closed-loop check on the accuracy of our location algorithms and the unique grid coordinate reference used at Yuma..

The 73.5 acre HULK3 site consisted of much more difficult terrain than the DRA site. In particular, there were numerous impassible washes cutting through the area. Both sites were covered by surveying the more accessible areas first, and then covering the remaining areas in order of difficulty as time permitted. HULK3 contained 119 marked grid squares, each 50 x 50 meters in size. Although the sticker bushes were not present at HULK3, more than 30% of the surface was covered with high concentrations of metal fragments from munitions fired at the site. These fragments were detected by both the GPR and EMS as surface targets and obscured the weaker real UXO targets buried beneath them.

Initially, each survey site was studied and a logical sequence of swath-painting tracks was established. On flat terrain, each grid square was covered with a sequence of parallel tracks. Five track per 25-meter grid were used on the DRA site and 11 tracks per 50-meter grid were used on the HULK3 site. Coverage of the grid was not constrained to linear tracks; triangular and U-shaped runs were used to fill in less-accessible areas. Figure 5 shows an overall plot of DGPS data from McChord.

OPERATIONAL SCENARIO - MCCHORD AFB

The McChord demonstration area also consisted of two sites; the North Site and the South Site. The 18.5 acre North Site contained 32 marked grid squares, each 50 x 50 meters. The North Site terrain was not flat and approximately 20% of the North Site was unnavigable due to dense trees. The two "known" and marked targets were located on the North Site. These targets were detected and located during normal collection runs. They were also the subject of several calibration runs to verify the accuracy of our target location algorithms.

The unusual shape of the South Site made difficult to estimate its exact size -- a little more than 41 acres is estimated. The grid was marked off in 50 x 50 meter squares.

While the terrain of the South Site, with the exception of the "pit" area, was topographically flat, a large portion of this area contained ground clutter (rubbish, trees, hidden and up-rooted stumps, stump holes, etc.,) making for some extremely rough going. About 15% of the South Site was unnavigable. Figure 6 provides a visual example of the conditions on the South Site.

The general grid coverage plan was generated on a daily basis, and updated as conditions and events dictated throughout the day. Our daily plan was coordinated with the other contractor working on the grid to ensure that we would not interfere with each other. A logical swath painting sequence was established but was difficult to maintain on the South Site due to the many obstructions.

The weather at McChord started out cold and rainy, with puddles adversely affecting the GPR collection. We then had a week of unusually clear weather, with the mornings extremely cold (high teens) with heavy frost. The heavy rains then returned and lasted throughout the remainder of the demonstration period.

The heavily wooded areas at McChord occasionally affected our RTKDGPS system as satellite views were blocked at times. In clear areas we occasionally experienced drop-outs due to marginal satellite constellation view angles (i.e., fewer than 4 satellites in view).

DATA COLLECTION

Given the large size of the demonstration areas an enormous amounts of multi sensor data was collected and stored on magnetic media. The fundamental philosophy of this multi-sensor collection system is the real time detection of UXO targets using a combination of GPR and EMS detections. When the UXO contaminated areas are as large as Yuma and McChord all raw data are recorded on magnetic disk and can be reprocessed off-line.

DATA PROCESSING

At Yuma, there was on-going confusion regarding the correct map coordinate system. This factor, along with the lengthy daily commute to and from the demonstration sites and other logistical shortcomings, precluded the on-site processing of collected data. The entire Yuma data base had to be processed at METRATEK's Virginia facility upon return from Yuma.

The ability to process data on a daily basis, on-site, at McChord greatly enhanced our data reduction effort. As a result we were able to meet the short-time data reporting requirements imposed by the demonstration sponsor.

Data Processing Software

All data processing is performed on IBM-compatible personal computers using in-house developed software. The software has been designed as a series of modular programs that generate data files for the next step in the process, and runs without operator intervention. Displays are provided to allow an operator to supervise the data processing and to detect any anomalies in the data by reviewing automatically generated hard copy plots. The modular processing programs include:

<u>EMS Processing.</u> This is a MATLAB data analysis program that provides automatic detection and thresholding of EMS targets and conversion of the raw sensor data into plots and listings of target detections, their strength and depth, and along track distance (location).

<u>DGPS processing.</u> This software is also written in MATLAB. It filters out the occasional bad data points (GPS drop-outs,) plots the target detections for each sensor on the grid, and calculates the along track distance data for correlation with the sensor data.

<u>Data Fusion.</u> This software combines the EMS sensor and GPS data, extracting target reports in spreadsheet format. This software is written in MATLAB.

<u>Synthetic Aperture Radar Processing.</u> This is part of the standard off-line data processing software package for the Model 200 radar. This software is written in FORTRAN, C and assembly language. This processing software provides along track images and target depth information for the GPR data collected from each of the three antenna pairs.

<u>Data Plotting.</u> This software plots the spreadsheet target data on grids corresponding to the demonstration site areas. These plots are produced using a combination of spreadsheet and PRESENTATIONS software.

The final product is a spreadsheet that includes all pertinent target location data. A diskette or a file suitable for forwarding over the INTERNET is also produced at this stage of the process.

Table 1 summarizes the coverage provided by the system at Yuma and MCCHORD. The peak data collection rate was 3.73 acres per hour (in flat terrain at Yuma) and the average over all four sites (174 acres) was 1.9 acres per hour.

CONCLUSIONS

We highly commend and appreciate the hard work and dedication shown by our hosts at Yuma and McChord, by NAVEOTECHDIV, and by PRC Environmental Management, Inc. personnel who managed the operations at both sites. Our experience at the Live Site Demonstrations at Yuma and McChord provided all of us with valuable insight into the real-life problems associated with the conduct of

large-scale UXO search operations.

These efforts demonstrate that a very small team can cover a large area of rough terrain in the relatively small amount of time allotted. For these tests, we perceived that it would be better competition-wise to cover as much area as possible than to do a more thorough job on a smaller area. For a real site, we would use a two-phase approach. The first (detection) phase would cover the grid in a timely manner. The collected data would then be analyzed on a daily basis to determine the location of suspect targets. The second (localization and identification) phase, which could be conducted by a second crew, would revisit detected target locations obtain more exact GPS coordinates, to differentiate UXO from trash, and to identify target attitude and type. We would also have an EOD team to clear obstacles and surface metal from areas where it exists in large quantities and from other areas as it is found. Finally, we would tailor the logistical support to the sensor portability to maximize the efficiency of the operation.

It is clear to us that to perform a proper job over a variety of terrain requires that the system be flexible enough to vary the swath easily, as this system demonstrated.

The data that we developed from these operations was"detection" data only. It not processed via target recognition algorithms because of time and lack of any "ground truth" data. Reliable identification and separation of UXO targets from non-UXO objects is a key need for proper use of this technology. We expect to address better target discrimination performance in the near future, after we receive the "known target " data from the government.

Table 1. Coverage Rate - Acres/hour

Day	Yuma DRA	Yuma Hulk	MCCHORD North	MCCHORD South
1	2.02	3.62	2.28	0.85
2	1.61	3.73	1.87	1.38
3	1.78	3.38	0.3	1.76
4	2.03	3.01		1.6
5	2.13	2.77		0.9
6		2.57		1.17
7		2.53		1.07
9				0.75
10				0.62
11				0.61
Average Rate	1.9	3.1	1.5	1.1
Total Acres	38.9	73.4	18.5	41.4
% Covered	85%	69%	80%	86%

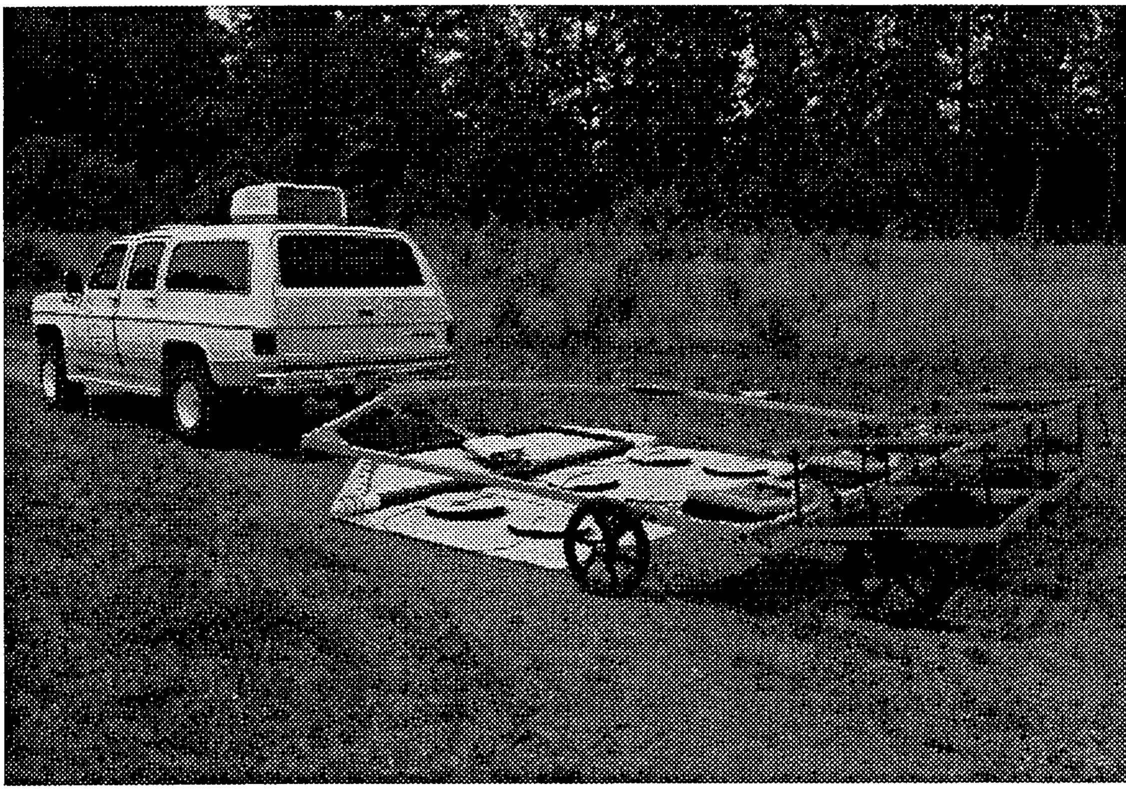

Figure 1. METRATEK UXO Detection System

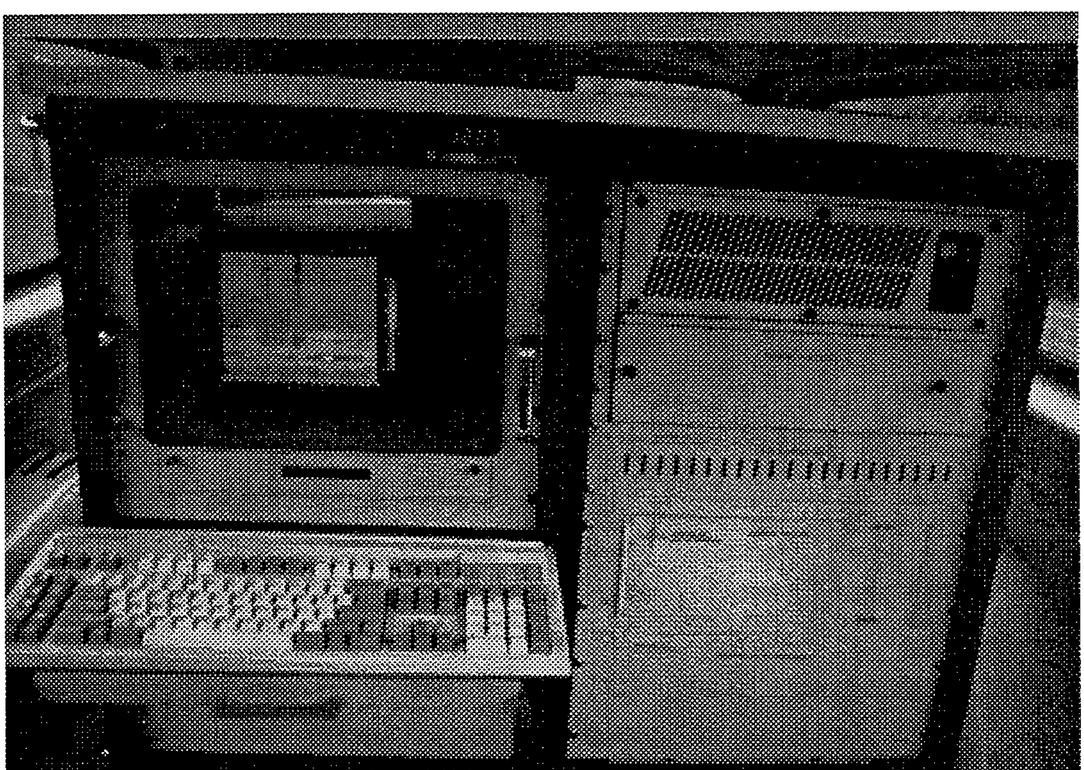

Figure 2. Model 200 SAR/GPR Installation and Display

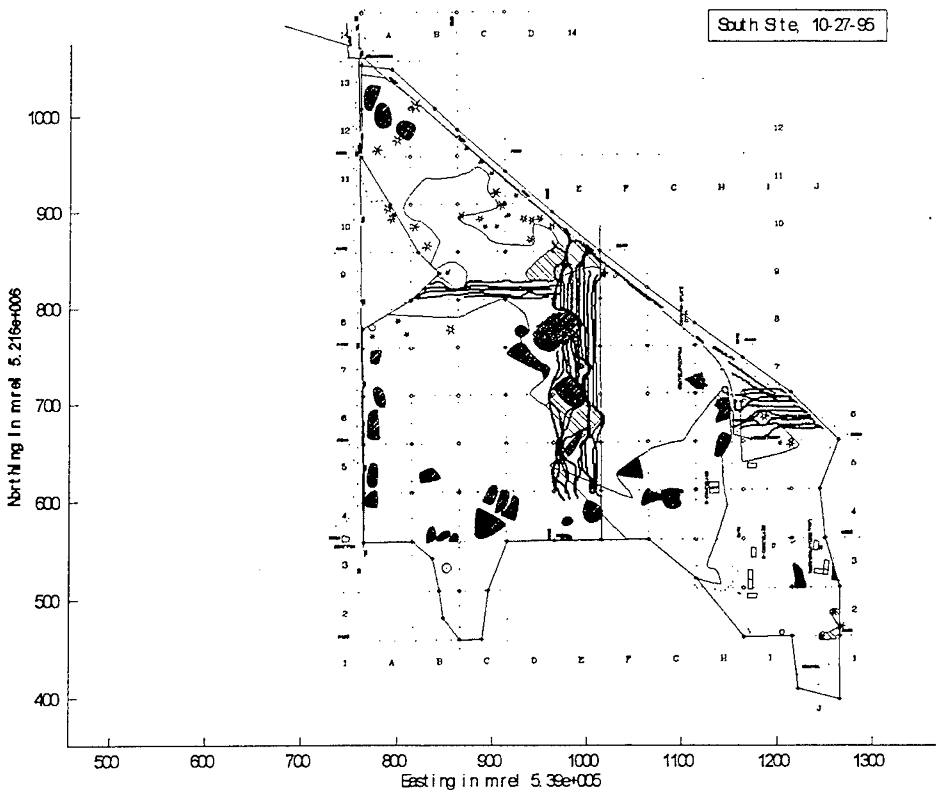

Figure 3. Typical DGPS Plot Showing Vehicle Track for One Day


Figure 4. Rough Terrain at McChord AFB Site

COMPUTER MODELING TO TRANSFER GPR UXO DETECTABILITY KNOWLEDGE BETWEEN SITES

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ABSTRACT

Using laboratory measurements on soils from Jefferson Proving Ground, Yuma Proving Ground, and Kaho'olawe Island, the ground penetrating radar response and detectability of buried objects (pipes, mines, etc.) have been modeled with a 2.5 dimensional program. The model parameters for the subsurface media are taken directly from frequency dependent laboratory measurements of the site samples. This allows the response of any object buried at one site to be simulated at another other site by changing the model parameters. Laboratory measurements also have been used to extend and test the range of applicability of ground penetrating radar by producing information about the variability of electromagnetic properties with depth, soil type, water content, temperature, and other variables. Combining this with the modeling program allows prediction of the detectability of objects at the same or different sites under varying conditions such as after a heavy rain, or at a different depth, in a new soil type, winter versus summer, or with other changing environmental and site variables.

The combination of this computer modeling program with material property information that is easily and inexpensively measured in the laboratory, allows not only the transfer of experience and knowledge from location to location. It also allows the rapid testing of hypotheses such as: What would be the detectability of plastic versus metal mines? What if they are buried deeper? What if the soil stratigraphy is slightly different or the water table is higher? What if the survey is performed in winter when the ground is frozen instead of summer? What size object could a UXO survey with these GPR parameters fail to detect under the specified conditions? Each of the example sites (Jefferson Proving Ground, Yuma Proving Ground, and Kaho'olawe Island) have very different site specific soil conditions requiring careful survey design for optimum detectability of unexploded ordnance.

DISPERSIVE MODELING

The modeling algorithm uses a hybrid of ray-tracing and boundary element methods to produce full waveform ground penetrating radar profile responses in a few minutes on desktop Pentium class personal computers. (Every synthetic radar profile shown in this paper was completed in less than 7 minutes on a desktop Pentium 133 MHz personal computer). A separate response is found for every significant frequency in the radar pulse, so the true, frequency dependent signatures of the media can be used. Conductivity, and complex functions of dielectric permittivity and magnetic permeability versus frequency as determined by the laboratory measurements are input to the modeling program. Zero-offset, primary reflections and multiples are modeled. The model is assumed to be infinite in the cross-profile direction, and the starting pulse is assumed to be polarized in this direction, so no polarization changes are considered. However, both amplitude and phase changes on the response due to attenuation and velocity variations with frequency are honored, as are complex reflection and transmission coefficients due to conductivity or other loss mechanism contrasts.

The measured, frequency dependent, electric and magnetic properties of a soil sample are input to the modeling program with the Cole-Cole parameters (Cole and Cole, 1941). The parameters are found for a given set of frequency dependent lab measurements by interactively matching the measured data to a Cole-Cole analytic response. This yields four parameters that describe the complex, relative dielectric permittivity as a function of frequency, and four similar parameters that describe the complex, magnetic permeability as a function of frequency. For a given soil, a single, static conductivity is also defined.

The Cole-Cole equation is:

$$\varepsilon_r'(\omega) - i\varepsilon_r''(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (i\omega\tau_\varepsilon)^{\alpha_\varepsilon}}$$

where ε_r' and ε_r'' are the real and imaginary parts of the relative permittivity, ε_s (static) is the real, relative permittivity at zero frequency, ε_∞ is the real, relative permittivity at infinitely high frequency, ω is the angular frequency, τ_ε is the time constant of relaxation determined by the various types of polarization processes taking place, and α_ε is the time constant distribution parameter that varies between 0 and 1. A similar equation can be written for the magnetic permeability. To give any material in the model a constant, frequency independent, value of permittivity or permeability, the values of ε_s and ε_∞ (or μ_s and μ_∞) are made the same.

With an analytical expression that gives material properties for any frequency, the velocity, attenuation, and reflection and transmission coefficients for every material and interface in the model can be found for a given frequency. The program then computes the entire model response for a single frequency. This is done for every significant frequency in the selected starting pulse, and the results are transformed back to the time domain for the final profile response. The details of this modeling algorithm can be found in Powers (1995).

YUMA PROVING GROUND

In the summer of 1993, airborne and ground penetrating radar data were collected at Yuma Proving Ground with a variety of systems (Ayasli et al., 1994). Figure 1a, the top image, is representative 500 MHz center-frequency impulse radar data (see Olhoeft et al., 1994) taken at Yuma over buried metal and plastic mines. Figure 1b, the bottom image, is synthetic radar data created using the modeling program described above and the electromagnetic parameters for the Yuma soil as listed in Table 1 and plotted in Figure 19 of Olhoeft et al. (1994).

The model, shown in Figure 2, includes the real, frequency dependent electrical and magnetic properties for the Yuma soil at the site where the mines were buried. Buried 25 cm deep within this soil are a metal and a plastic mine. A simple geological layer of higher dielectric permittivity and variable thickness (1-4 cm) exists below the mines. No detailed geological statistical variations or heterogeneities are included. The response is quite sensitive to the shape of the buried mines, which are 40 cm wide with a centered dome-shaped top 19 cm in diameter. Figure 1 is presented to validate the model against real field data.

Figure 3 shows an entirely fictitious, generic model of three pairs of buried metal and plastic mines at increasing depths of 15, 30, and 45 cm. This model is used for the different sites to illustrate the effects of water content and varying site soil conditions on mine detection. The two images of Figure 4 show responses to this generic model with the Yuma soil for the two measured amounts of natural water content (0.29 and 1.31 weight percent) found at this site. The complete soil parameters used to generate these images are given in Table 2, and are also plotted as Figures 19 and 20 of Olhoeft et al. (1994). Note how the increased water content causes increased attenuation so the deepest metal mine disappears but the shallowest plastic mine becomes more visible due to the better dielectric contrast between the mine and the wetter soil. These images are shown as raw data profiles without synthetic aperture (velocity migration) processing. The dispersive (frequency dependent) soil properties can cause summation of the scattering hyperbola to result in defocusing, possibly making the images worse if processed (see example in Figure 44 of Powers, 1995).

JEFFERSON PROVING GROUND

Four samples from the Jefferson Proving Ground (supplied by John Rupp of the Indiana Geological Survey) were each measured at three water contents. All four were remarkably alike, with magnetic properties of free space. Figure 5 shows synthetic radar images created using the electrical properties plotted in Figure 6 and parameterized as listed in Table 3. Note how the increased water content in the lower image results in increased detection of the two shallowest plastic mines but less detection for the deepest metal mine. These laboratory measurements were made at room temperature, but would exhibit significant reductions in permittivity, conductivity, and resultant losses if frozen. This would mean better and deeper detection for the metal mines but worse detection for the plastic mines in frozen conditions. This indicates that the sensitivity of ground penetrating radar to the detection of buried objects at Jefferson Proving Ground is a highly sensitive function of environmental parameters (rainfall and season) that could help explain some of the results in the recent test of GPR methods at this site.

KAHO'OLAWE ISLAND

Kaho'olawe Island samples were collected in 1979 by Gary Olhoeft during a cooperative investigation of the island jointly performed by the U.S. Geological Survey, Denver, CO, and the U.S. Navy EODTECHCEN, Indian Head, MD. The magnetic susceptibility of the 25 samples collected varied by a factor of 70 from the nearly non-magnetic beach sand to the highly magnetic altered basalt- and ash-fall-derived soils. Several samples exhibited an anomalous radio-frequency magnetic loss mechanism that has also been observed from samples at Yuma (Olhoeft and Capron, 1993, 1994).

Using the properties plotted in Figure 7 and parameterized as listed in Table 4, Figure 8 shows synthetic radar images of the metal and plastic mines buried in Kaho'olawe beach sand. The dry sand radar image clearly shows the metal mines at all three depths, but the addition of 16.4 weight percent water improves the detection of the plastic mines while decreasing the detection of the metal mines.

SUMMARY

This paper illustrates the use of laboratory measurements and simple, fast computer modeling to predict the detectability with ground penetrating radar of buried metal and plastic mines. As evidenced by the examples shown with varying water content, simple variations in common environmental variables (water content, temperature, surface conditions for antenna coupling) can have a dramatic effect on the detectability of buried mines. Soil type variations (sand, clay, iron content) can have further dramatic effects, as can the site-specific settings of frequency and gain. All of these can be explored efficiently with laboratory measurements and simple modeling.

ACKNOWLEDGMENTS

The Kaho'olawe field work and sample collection were funded by NAVEODTECHCEN under the direction of Jim Hershey through a Military Interagency Procurement Request to the U.S. Geological Survey in 1979. The Yuma field and laboratory investigations were funded by the Central MASINT Office (CMO) of DIA under the direction of George Andreiev through a Military Interagency Procurement Request to the U.S. Geological Survey in 1993. The current modeling effort and the laboratory measurements on the Jefferson Proving Ground and Kaho'olawe samples were funded by a Colorado School of Mines discretionary account.

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Table 1. The media parameters for the Yuma model of Figure 2 and the response shown in Figure 1b.

Media	ε_S	ε_∞	$\tau_\varepsilon \times 10^{-9}$ sec	α_ε	μ_S	μ_∞	$\tau_\mu \times 10^{-9}$ sec	α_μ	σ_S mS/m
Top layer	4.37	3.08	14.1	0.60	1.16	1.03	15.0	1.00	0.217
Thin layer	27.8	15.3	7.5	0.64	1.20	1.06	15.0	1.00	50.8
Bottom layer	4.37	3.08	14.1	0.60	1.16	1.03	15.0	1.00	0.217
Metal mine	42.0	16.0	11.0	0.62	100	10.0	0.64	0.90	10^7
Plastic mine	2.80	2.80	0	1.00	1.00	1.00	0	1.00	0

Table 2. Yuma Proving Ground soil sample electrical properties from laboratory measurements of buried mine site samples.

Weight % Water	Bulk density gm/cm^3	Conductivity mS/m	Lo frequency dielectric permittivity ε_s	Hi frequency dielectric permittivity ε_∞	Cole-Cole time relaxation constant $\tau_r \times 10^{-9}$sec	Cole-Cole distribution parameter α_r	Magnetic permeability μ
0.29	1.49	0.217	4.37	3.08	14.1	0.60	1.0
1.31	1.36	15.4	9.18	3.30	7.50	0.64	1.0

Table 3. Jefferson Proving Ground soil sample electrical properties from laboratory measurements.

Weight % Water	Bulk density gm/cm^3	Conductivity mS/m	Lo frequency dielectric permittivity ε_s	Hi frequency dielectric permittivity ε_∞	Cole-Cole time relaxation constant $\tau_r \times 10^{-9}$sec	Cole-Cole distribution parameter α_r	Magnetic permeability μ
0.0	1.18	0.286	5.77	2.98	8.00	0.62	1.0
13.2		12.1	34.1	9.70	10.9	0.72	1.0

Table 4. Kaho'olawe Island beach sand electrical properties from laboratory measurements.

Weight % Water	Bulk density gm/cm^3	Conductivity mS/m	Lo frequency dielectric permittivity ε_s	Hi frequency dielectric permittivity ε_∞	Cole-Cole time relaxation constant $\tau_r \times 10^{-9}$sec	Cole-Cole distribution parameter α_r	Magnetic permeability μ
0.0	1.64	<0.20	3.83	3.70	8.00	0.70	1.0
16.4		41.7	23.2	18.2	12.5	0.70	1.0

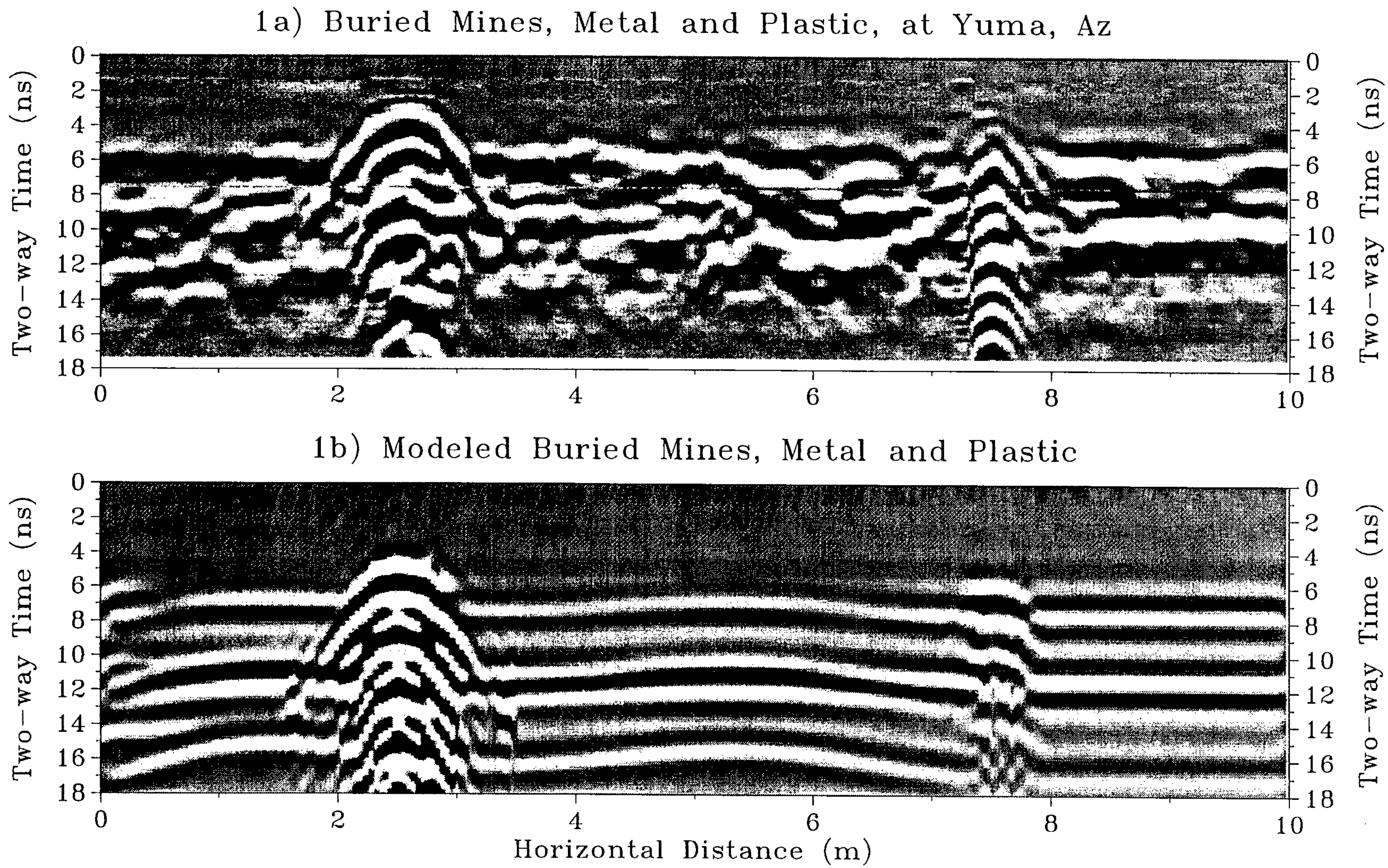

Figure 1. a) 500 MHz field data over a buried metal and plastic mine at the Yuma Proving Ground. b) Synthetic model data using the model of Figure 2 and the parameters listed in Table 1.

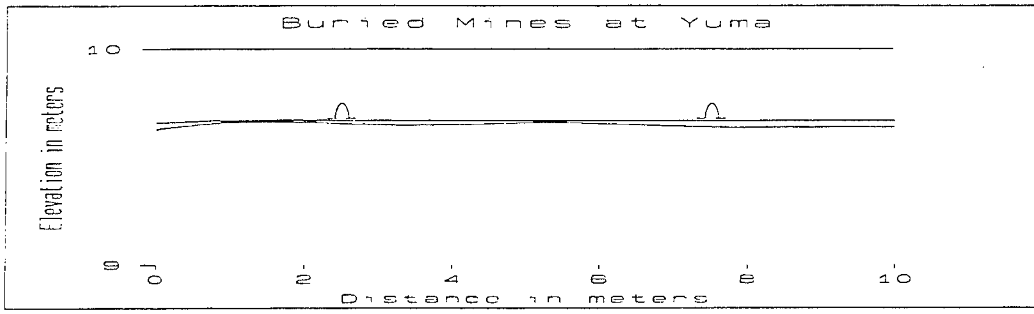

Figure 2. The model of a buried metal and plastic mine at the Yuma, AZ, site. Note the vertical exaggeration in this figure. The response to this model is shown as Figure 1b. The material parameters are shown in Table 1.

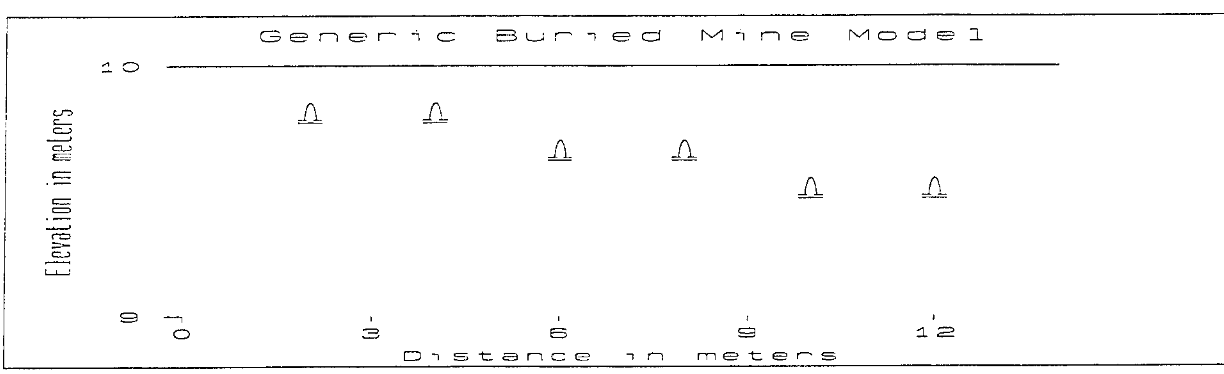

Figure 3. The model of three pairs of metal and plastic mines buried at 15, 30, and 45 cm depth. Note the vertical exaggeration in this figure. This generic model is used with varying soil properties to simulate different sites and variable conditions (wetter or drier). The images of Figures 4, 5, and 8 are all responses to this model with different soil properties. The properties used for the metal and plastic mines are shown in Table 1.

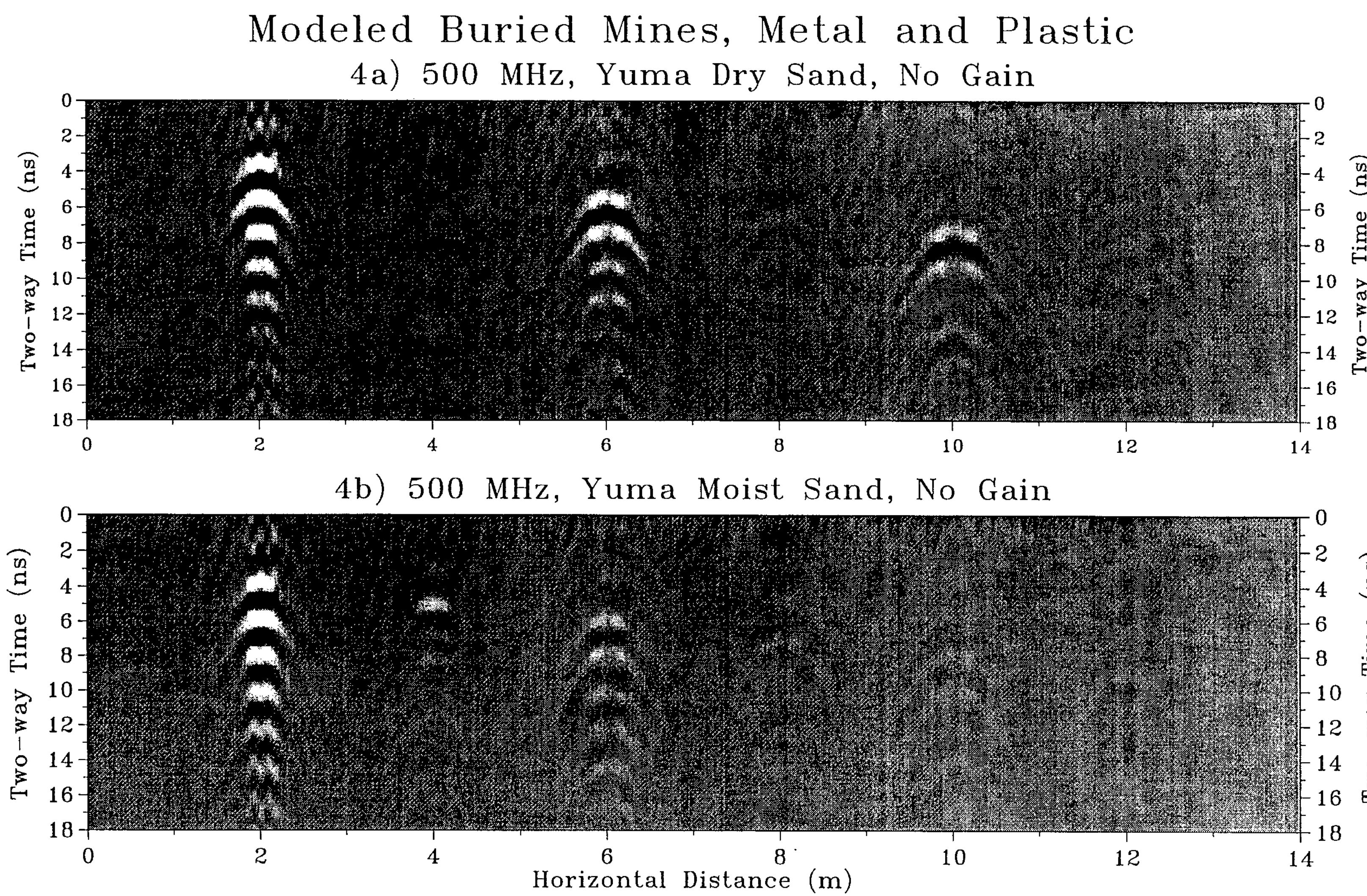

Figure 4. a) Model response of alternating metal and plastic mines buried in dry Yuma sand. The three metal/plastic pairs are buried at 15, 30, and 45 cm depth. b) Same model using properties of moist Yuma sand collected at .5m depth. The soil parameters are in Table 2.

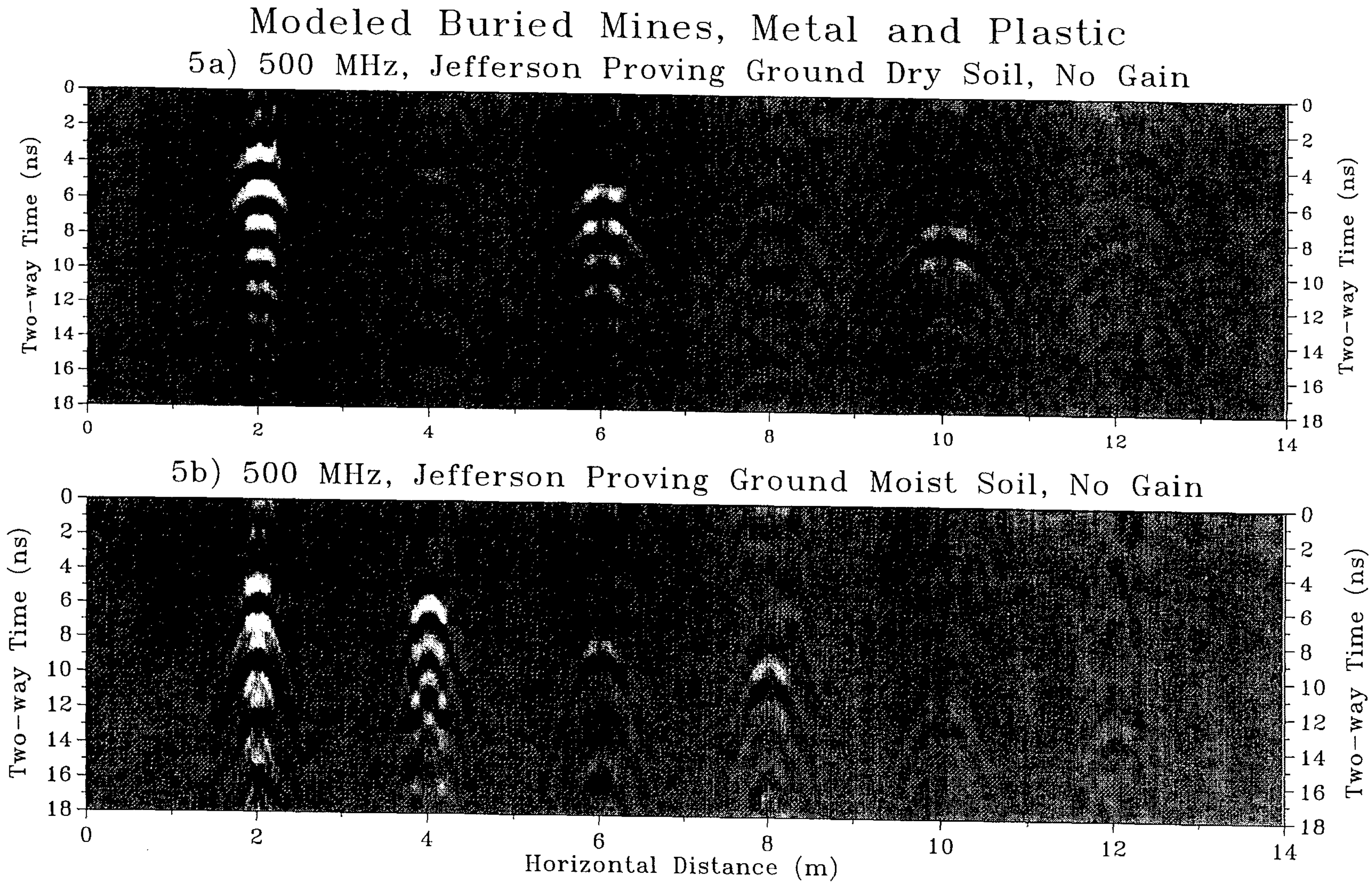

Figure 5. a) Model response of alternating metal and plastic mines buried in dry JPG soil. The three metal/plastic pairs are buried at 15, 30, and 45 cm depth. b) Same model using properties of moist JPG sand. The soil parameters are in Table 3.

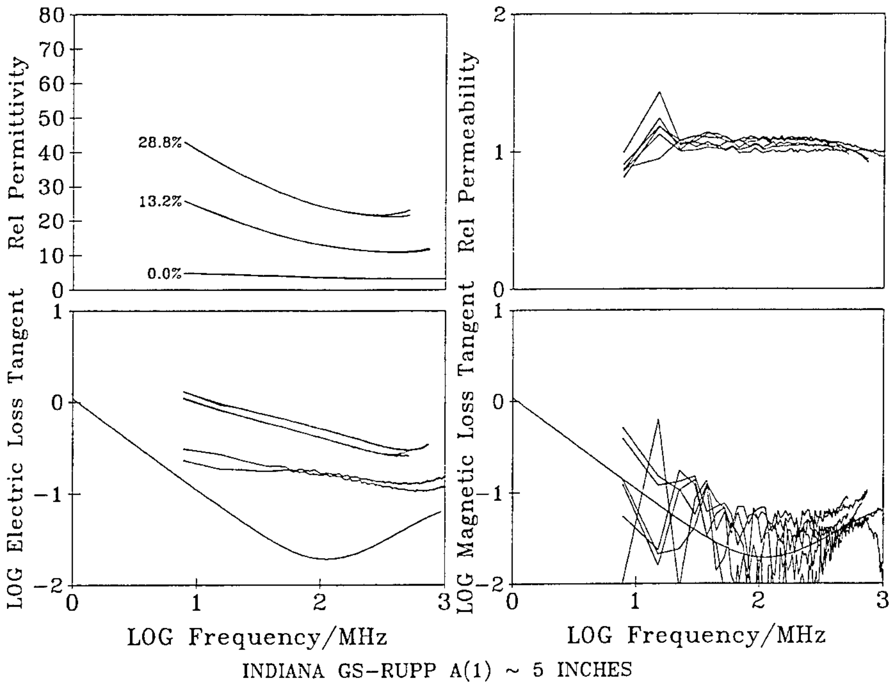

Figure 6. The laboratory measurements of electromagnetic soil properties of three samples from Jefferson Proving Ground, Indiana (samples provided by John Rupp, Indiana Geological Survey, 1993). For each sample, data are acquired twice, once through each end of the sample. The smooth line on each loss tangent plot with a minimum at 100 MHz is the lower limit of reliable measurement of the loss tangent for the instrument.

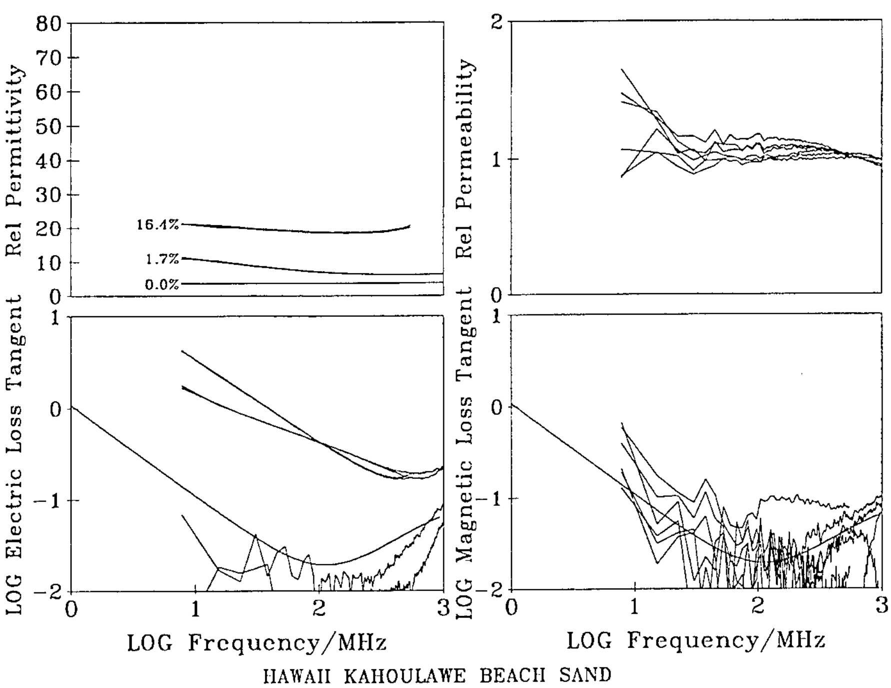

Figure 7. The laboratory measurements of electromagnetic soil properties of beach sand from Kaho'olawe Island, HI (sample collected by G. Olhoeft in 1979).

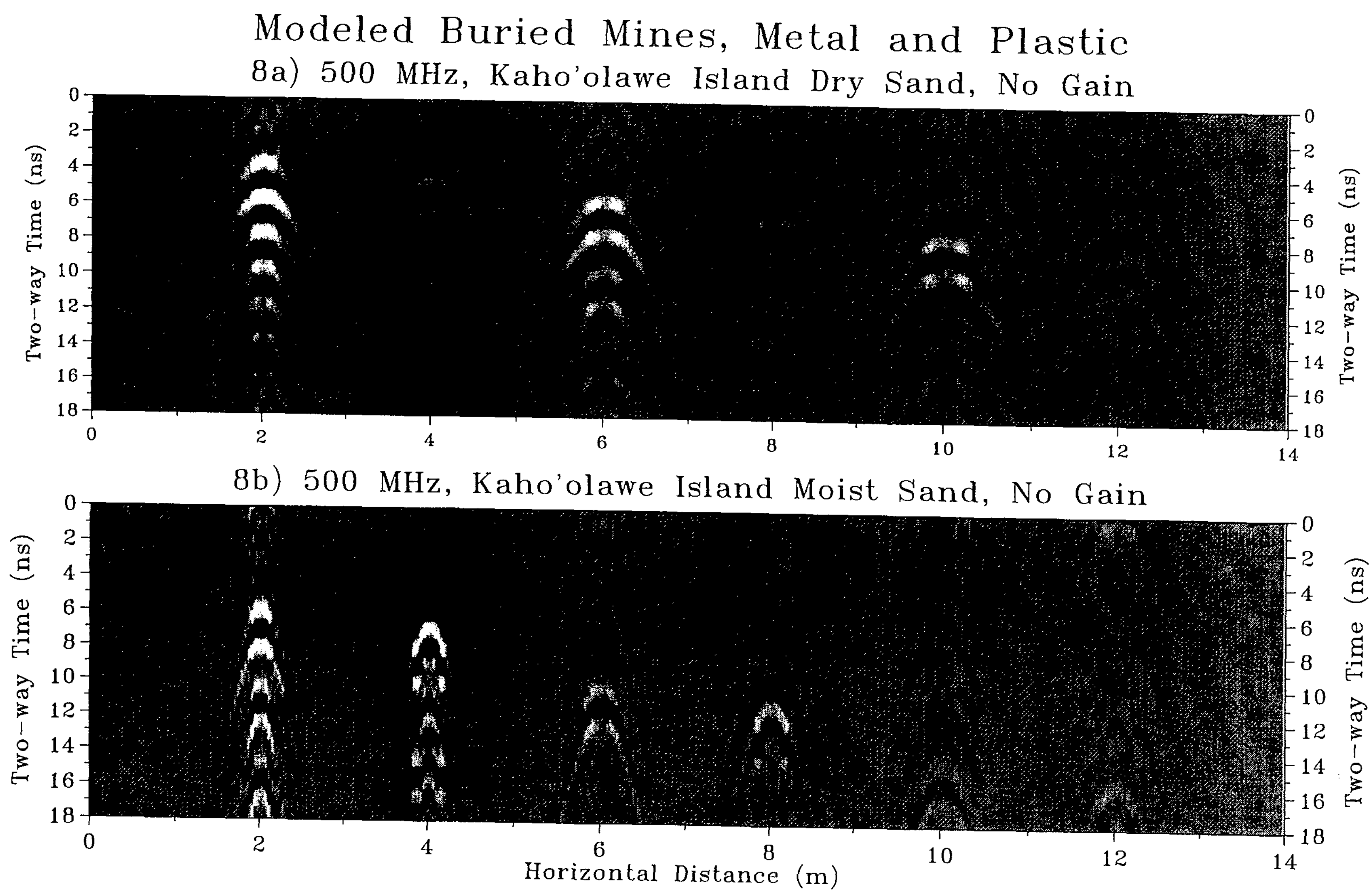

Figure 8. a) Model response of alternating metal and plastic mines buried in dry Kaho'olawe Island beach sand. The three metal/plastic pairs are buried at 15, 30, and 45 cm depth. b) Same model using properties of moist beach sand. The soil parameters are in Table 4.

REAL-TIME MAN-PORTABLE GROUND-PENETRATING SYNTHETIC APERTURE RADAR

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ABSTRACT

METRATEK, Inc. has developed a Real-Time Man-Portable Ground-Penetrating Synthetic Aperture Radar (RTMPGPSAR) as a demonstration system for the U.S. Army Environmental Center under contract to the Naval Ordnance Disposal Technology Division. The system consists of a METRATEK Model 200 radar adapted for use with backpack radar electronics, an antenna sled that is pushed along the ground, and real-time software developed for the Advanced-Adaptive-Image-Processing-for-Real-Time-Man-Portable-Synthetic-Aperture-Radar program to provide the operator with an image of buried targets as he moves along the ground. This paper describes the system and test results obtained with it.

INTRODUCTION

METRATEK demonstrated real-time imaging with a man-portable radar using an existing METRATEK Model 200 radar. The Model 200 is a high-sensitivity step-chirp imaging radar that has been extensively used to perform SAR radar cross section measurements of low-observable aircraft, including air-to-air images. For this effort, the radar was augmented with a man-portable antenna system and a real-time synthetic aperture processing system using a laptop computer. This is referred to as the RTMPGPSAR Demonstration system.

RADAR PROCESSING

Step-Chirp Waveform

Impulse waveforms have been a mainstay of GPR technology for many years, but have not been able to provide really satisfactory performance for a variety of reasons, including the difficulty of providing the many fast range samples needed to capture the energy in every resolution cell, lack of control of the waveform, and difficulty of coherent (SAR) processing. Our approach to GPR was to try to exploit the advantages of a step-chirp waveform, where we have coherent pulses, close control of the amplitude and phase of every frequency, and the ability to generate range resolution cells via simple Fourier transform processing (to implement a matched-filter correlation process) without requiring separate single range gates for every resolution cell.

SAR Processing

The SAR (cross-range) processing is performed by calculating the radar return from a point scatterer over several down-range samples and convolving the result with the actual down-range samples. The result is a matched filter that produces the Radar Cross Section (RCS) value of any point. This accurately produces a radar image of RCS values versus down-range (depth) versus cross-range (distance traveled along the ground).

Figure 1 illustrates the standard SAR configuration used in GPR. The antennas are moved along the ground, triggering the radar to chirp pulse at a preset interval. The radar illuminates the target several times as the target passes through the beam. The number of "hits" is determined by the beam width. The pulse width and sample range determine the range of depths.

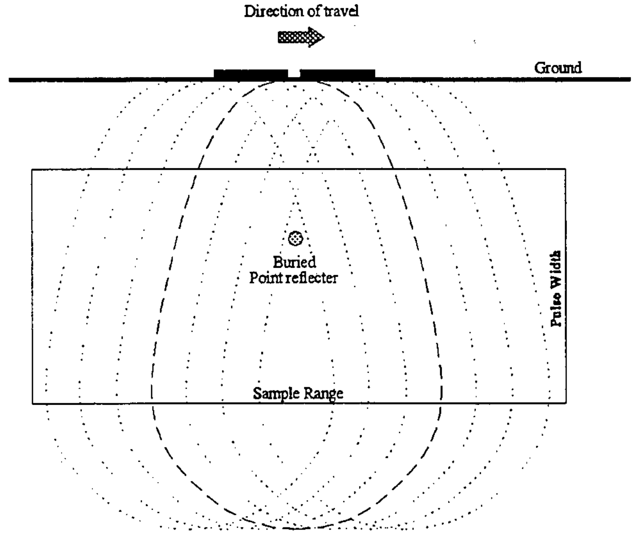

Figure 1. Standard SAR Configuration

Figure 2 illustrates the range to the point reflector as it moves through the beam. Notice the parabolic shape. The minimum range is achieved when the reflector is directly below. Because the range is calculated by time, it is dependant on propagation speed or the refractive index. The dotted lines signify the down-range resolution. The actual return would be a sin(x)/x pattern with 3 dB points at the dotted lines.

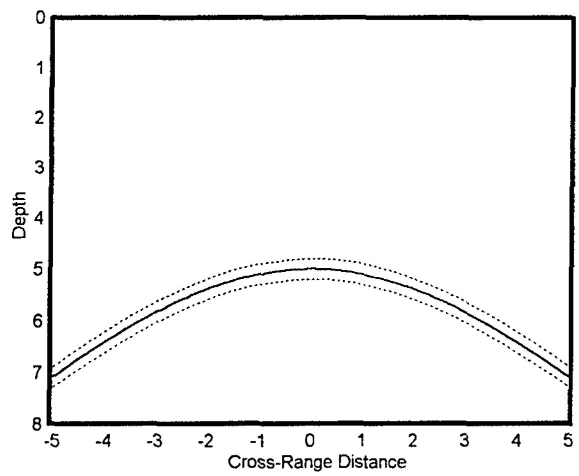

Figure 2. Down-Range Data

An actual object (or objects) would represent multiple point reflectors, and, therefore, would be seen in down range as multiple parabolas interfering with each other. In order to resolve an image, these returns are SAR processed. **Figure 3** illustrates the SAR image of an ideal point reflector. The SAR matched filtering is performed by calculating the theoretical phase pattern of a point reflector in every range cell (point in the down-range FFT). The result is convolved with the radar data, focussing the data to a single point with width equal to the cross-range resolution. The result is a star-like return with width and height determined by cross-range and down-range resolution respectively.

SYSTEM ARCHITECTURE

METRATEK-owned and -modified equipment demonstrates real-time SAR processing of GPR data. This is accomplished by networking the existing Model 200 radar computer with a Pentium laptop computer. The laptop receives integrated and calibrated raw data from the Model 200 DSP hardware, computes the down-range and SAR image in a strip-map fashion, and displays the results to the man-portable operator.

The bulk of the Model 200 radar is housed in a four-wheel-drive vehicle equipped with generated power for all subsystems. A 30-foot cable connects the radar subsystem to the man-portable subsystem and the SAR-processing subsystem.

The man-portable subsystem consists of a sled containing two space duplexed antennas, and a backpack containing the RF electronics. The sled is equipped with wheels that serve two purposes: to allow easy transport of the sled when the wheels are swiveled beneath the sled, and to trigger the radar at fixed intervals when the sled is operated. The RF data is sent through the cable to the Model 200 radar.

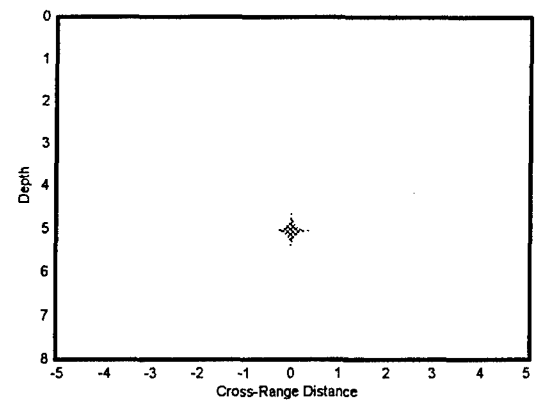

Figure 3. Cross-Range Processing

The SAR-processing subsystem is a laptop computer in the backpack. A network sends the raw data from the Model 200 radar computer to the laptop. The user interface includes a touch pad as a pointing device and a visor as a sunlight readable color display.

A block diagram of the complete system is shown in **Figure 4**. A photograph of the system is shown in **Figure 5**. This architecture was intended to use existing radar hardware as a platform for feasibility testing. Future system architectures will miniaturize the radar subsystem to allow a truly man-portable system.

REAL-TIME DISPLAY

Previously, SAR imaging was produced off-line using SAR-station software. These algorithms were altered to create a real-time imaging system capable of reading data from a network (real-time imaging) or from data files (off-line imaging).

The real-time software receives real-time data over the network hardware from the Model 200 software. It reduces the down-range data and displays the results. It additionally calculates and displays the SAR image. Both of these displays are shown in strip-map format that scrolls to allow infinite cross-range distances. The SAR baseline is selected at a fixed size based on the number of expected hits on a target.

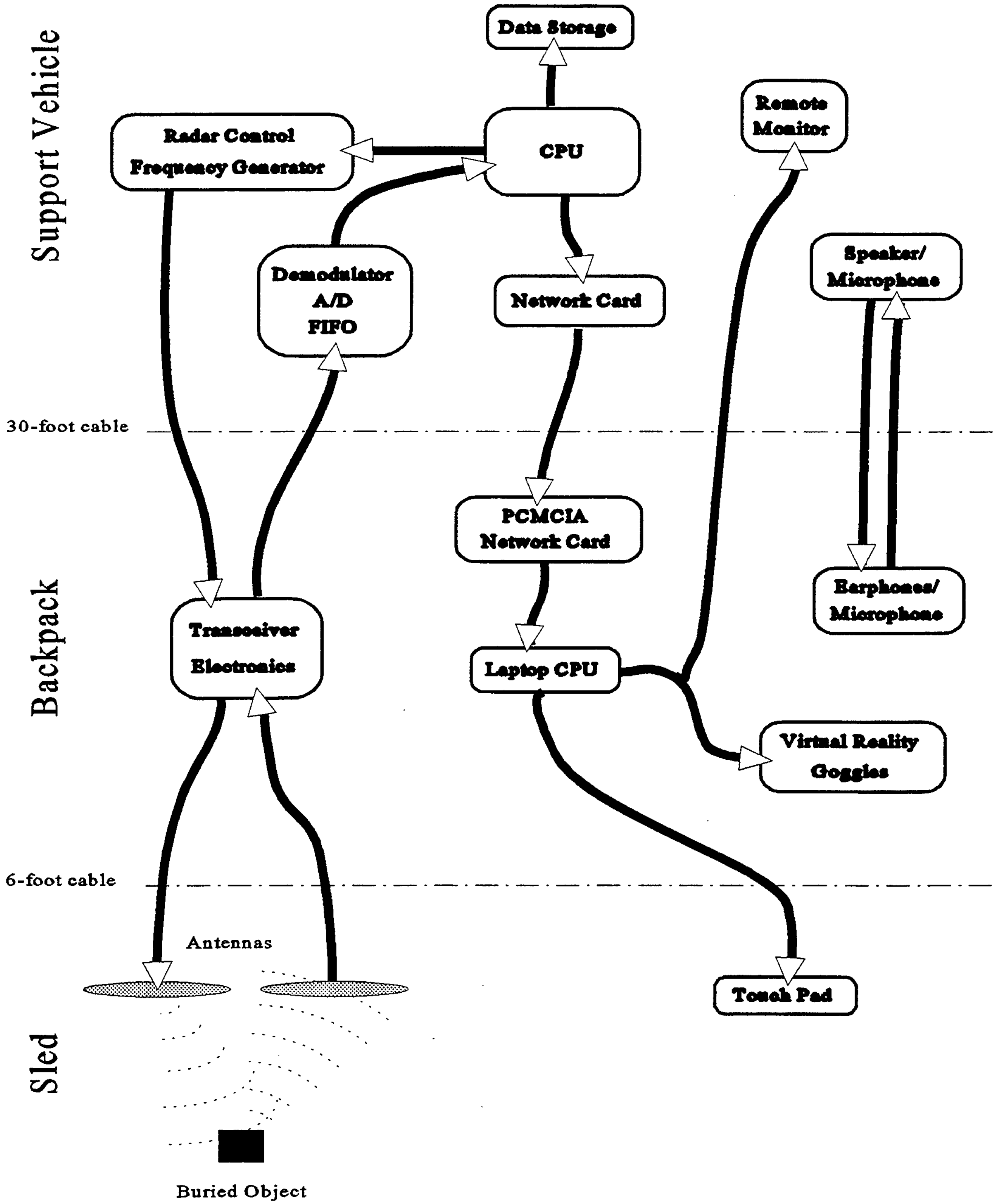

Figure 4. System Block Diagram

Figure 5. RTMPGPSAR Demonstration System

RESULTS

The RTMPGPSAR system was tested and demonstrated in various soils. Table 1 shows the qualitative system results at the various sites tested. The NAVEODTECHCEN magnetometer calibration range was used during system and software development. Because no real-time display was available, the analysis was conducted using traditional off -line processing. The waveform used during these tests failed to include the shallow (less then 2 feet) targets. The testing at Tyndall AFB was to obtain the bulk of data for the final system. These tests were postponed because of Hurricane Opal. The handful of tests on known targets were completely successful.

Table 1. RTMPGPSAR Test Results

Location	Soil Type	Known Targets Detected	Unknown Targets Detected
NAVEODTECHCEN Magnetometer Range	Sand	67%	N/A
NAVEODTECHCEN Clay Test Range	Clay	N/A	100%
Tyndall AFB Test Bed	Sand	100%	TBD*

*Test postponed due to inclement weather

CONCLUSIONS

The RTMPGPSAR system successfully demonstrated imaging of submerged ordnance in real time. It showed the ability to instantaneously locate buried ordnance. The ability to identify and classify submerged ordnance shows promise with additional data.

System Integration

Because of the modular design of the real-time SAR processing computer, the system may be easily integrated into other GPR systems at the subsystem level to obtain real-time results. The subsystems unclude the antennas, the Model 200 radar, and the real-time SAR processor and display.

System Improvements

The system network will be replaced with a cordless link to separate the operator from hazardous areas. Additionally, the Model 200 radar system will be miniaturized as a general purpose radar subsystem for production units.

A PRESENTATION BY FOERSTER

HANNS-PETER TRINKAUS
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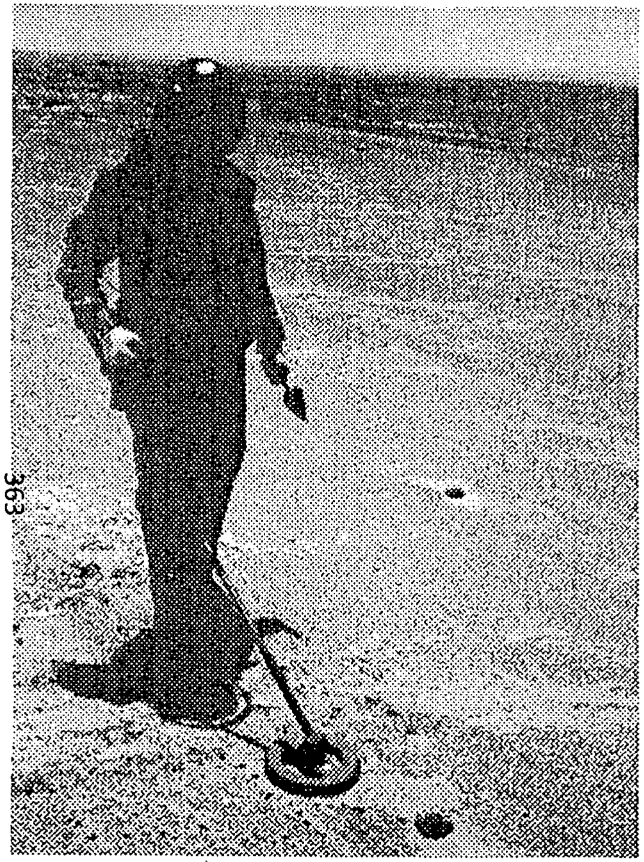
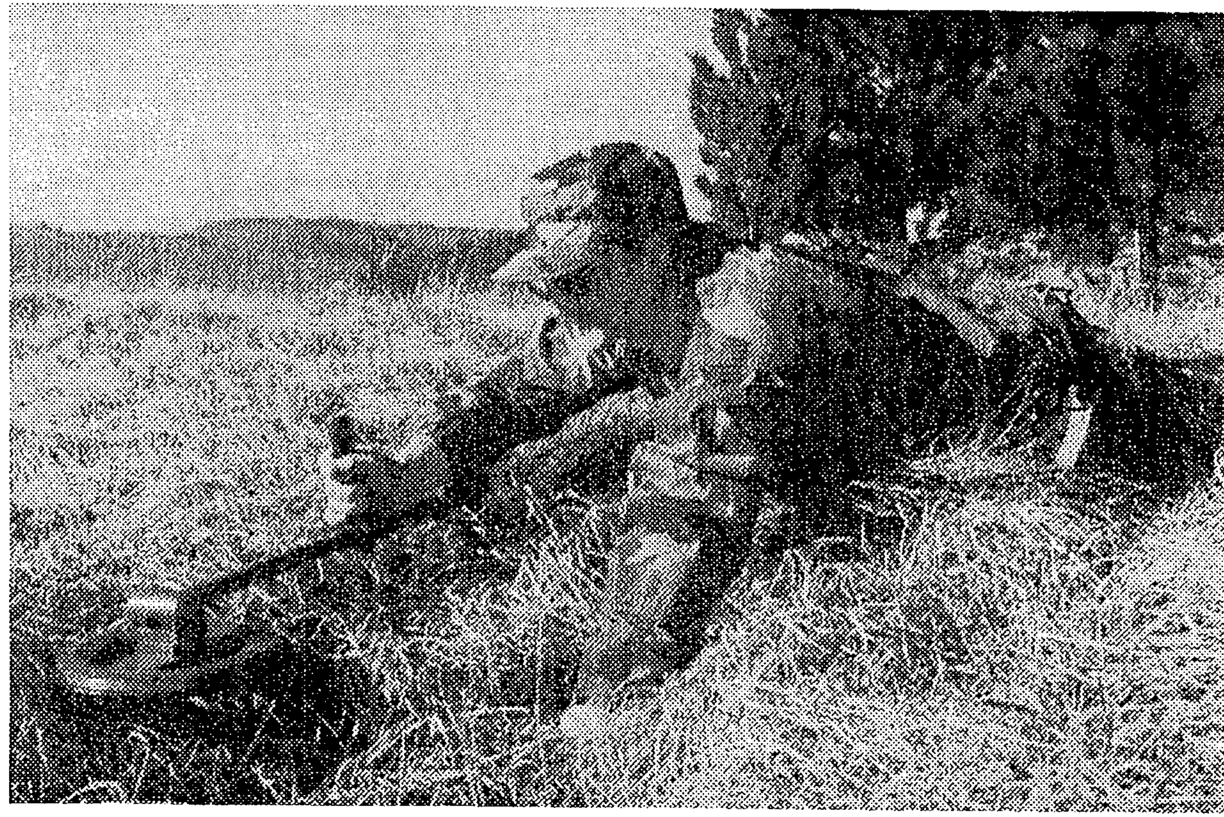
The EOD/OEW Community respect the Forester name, recognize Foerster for providing superior search instruments and gain the added benefit of Foerster's devotion to excellence and growth in the sensor/detector technology field.

The following pages are a first in a series, explaining the principle of the low metal mine detectors: MINEX 2FD and MINEX 2000SL, for both hand held as well as systems integration purposes. The characteristics of these dual frequency, continuous wave instruments are a patented detection system developed by Foerster which have proven very beneficial all over the world, even in areas such as Hawaii and Cambodia where the magnetic soil content level is very high. The information you are about to read will satisfy many questions as to what is currently available, off the shelf, through Foerster. As the cost of reinventing the wheel isn't in many budgets, please review and digest what Foerster has to offer. We welcome your inquiries of how Foerster can satisfy your mine, ordnance and explosive waste detection needs. For more information, please contact Foerster.

The Foerster MINEX Dual Frequency Detector represents the latest state of the art in sensor technology, signal-evaluation and -processing.





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Foerster MINEX® Technology

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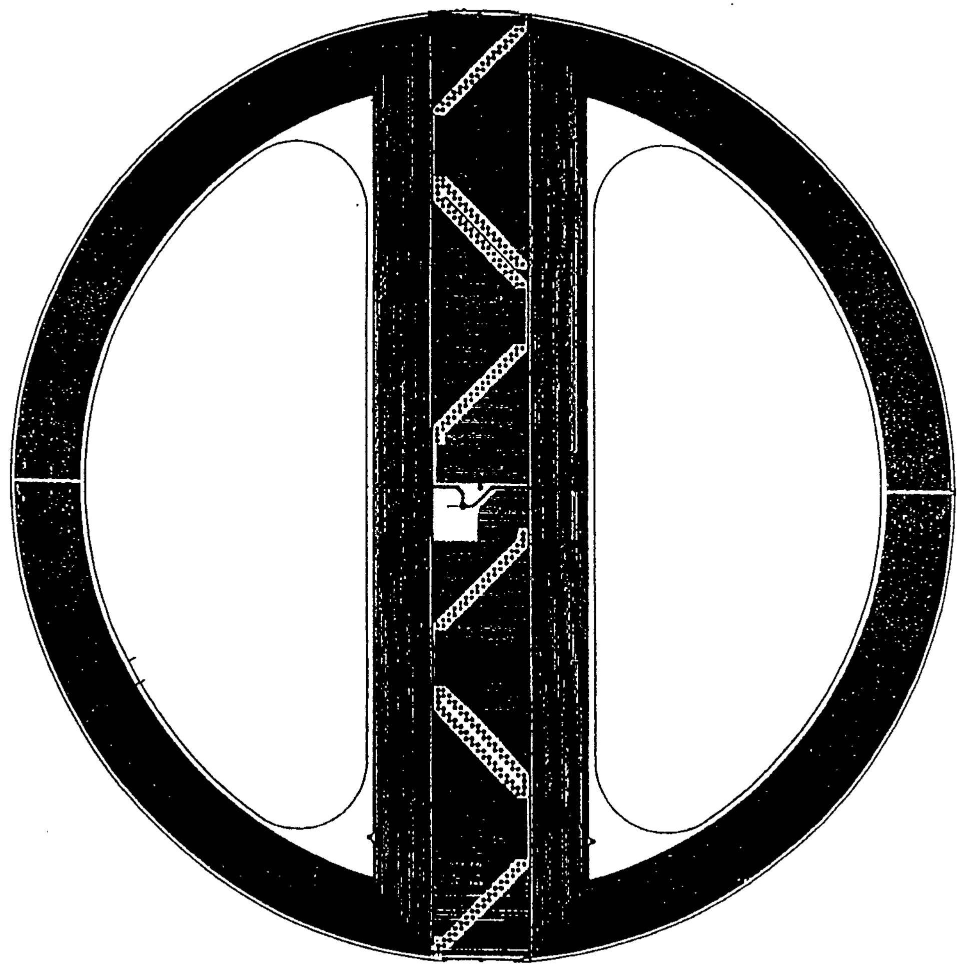
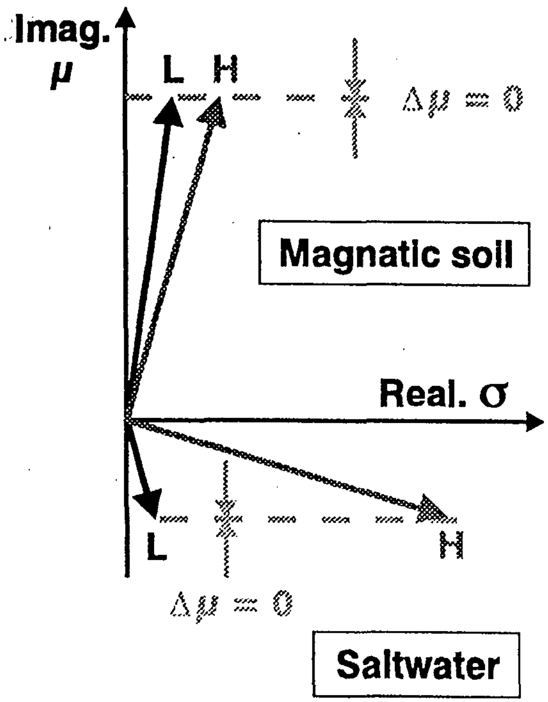
MINEX Sensor Systems

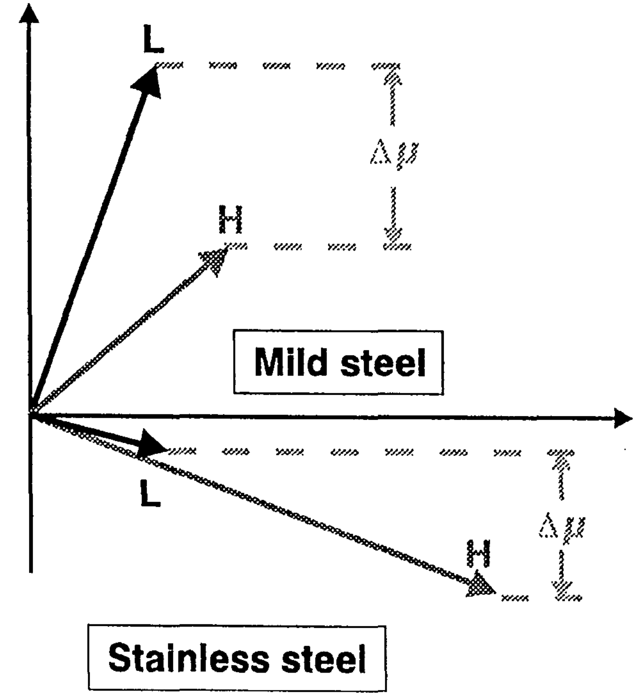
The MINEX Sensor System is built up by one transmitter coil and a set of PCB-type multilayer receiver coils in differential (gradiometer) configuration.



Each sensor half (left and right) produces a different audio signal frequency or voltage output with plus/minus polarity respectively. The "Zero" middle line serves for extremely exact pinpointing.

MINEX Two Frequency Signal Evaluation





L: Impedance at lower frequency
H: higher frequency

The two MINEX frequencies are transmitted and received continuously and simultaneously.

The signal evaluation method is microprocessor controlled. Whereas the response from all kind of metal is clearly differentiated, disturbing influences are automatically made "Zero".

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Foerster MINEX® Technology

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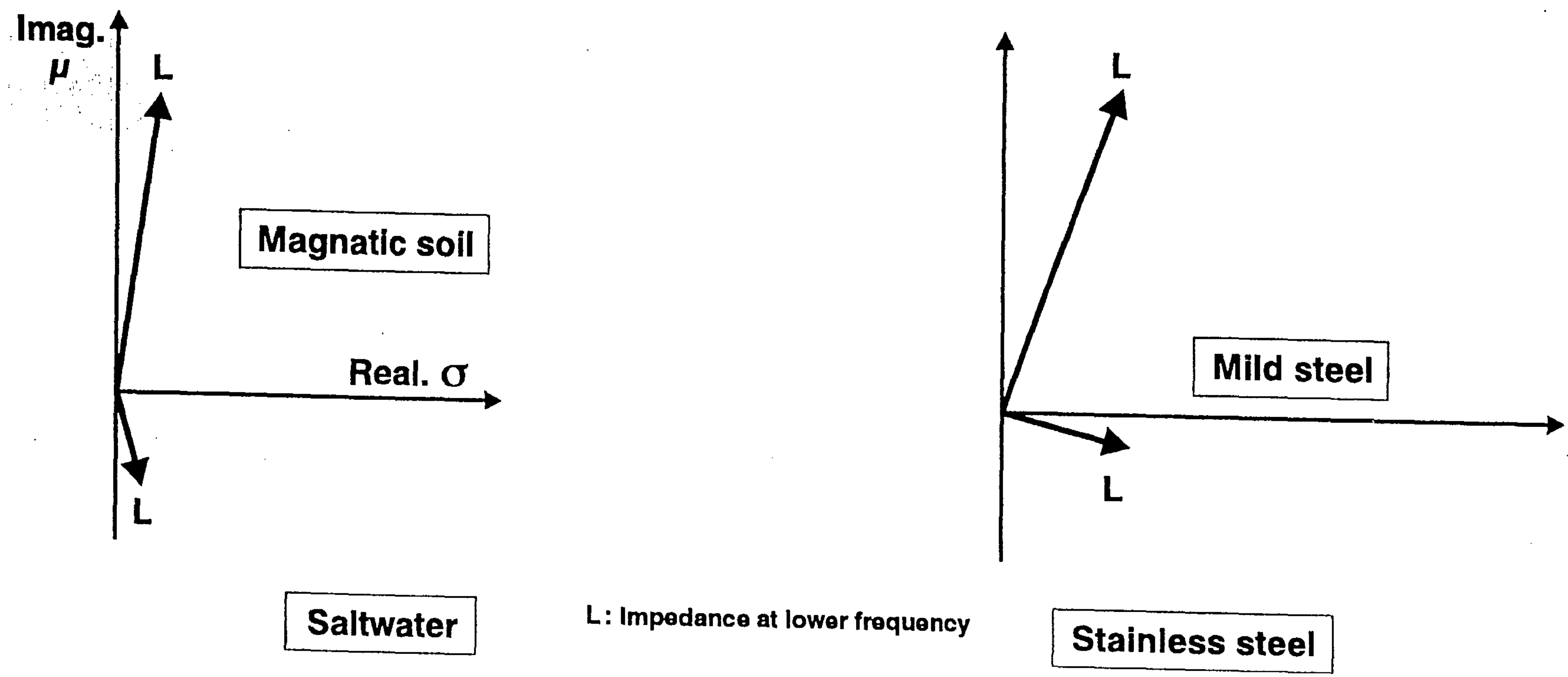
MINEX Two Frequency Signal Evaluation



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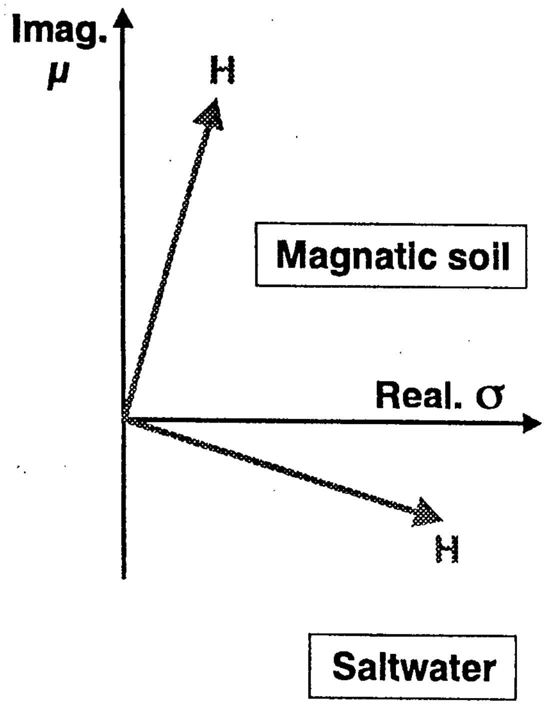
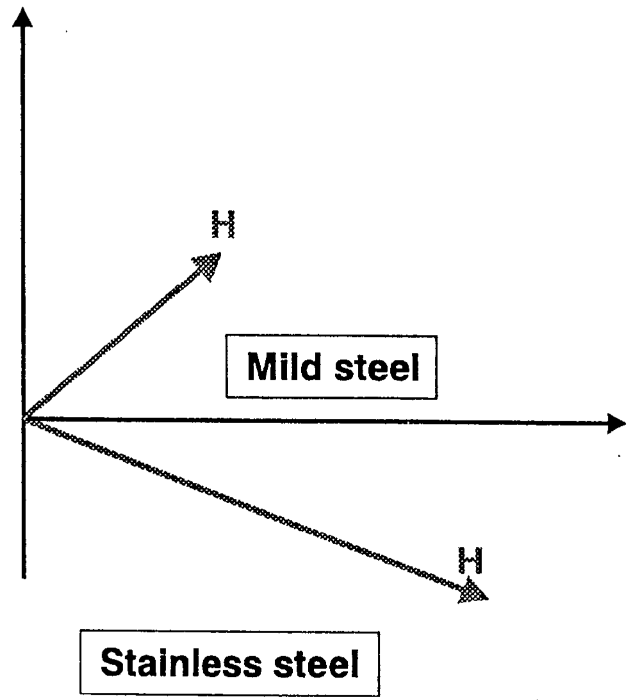
MINEX Two Frequency Signal Evaluation





H: higher frequency

The two MINEX frequencies are transmitted and received continuously and simultaneously.

The signal evaluation method is microprocessor controlled. Whereas the response from all kind of metal is clearly differentiated, disturbing influences are automatically made "Zero".

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4.H

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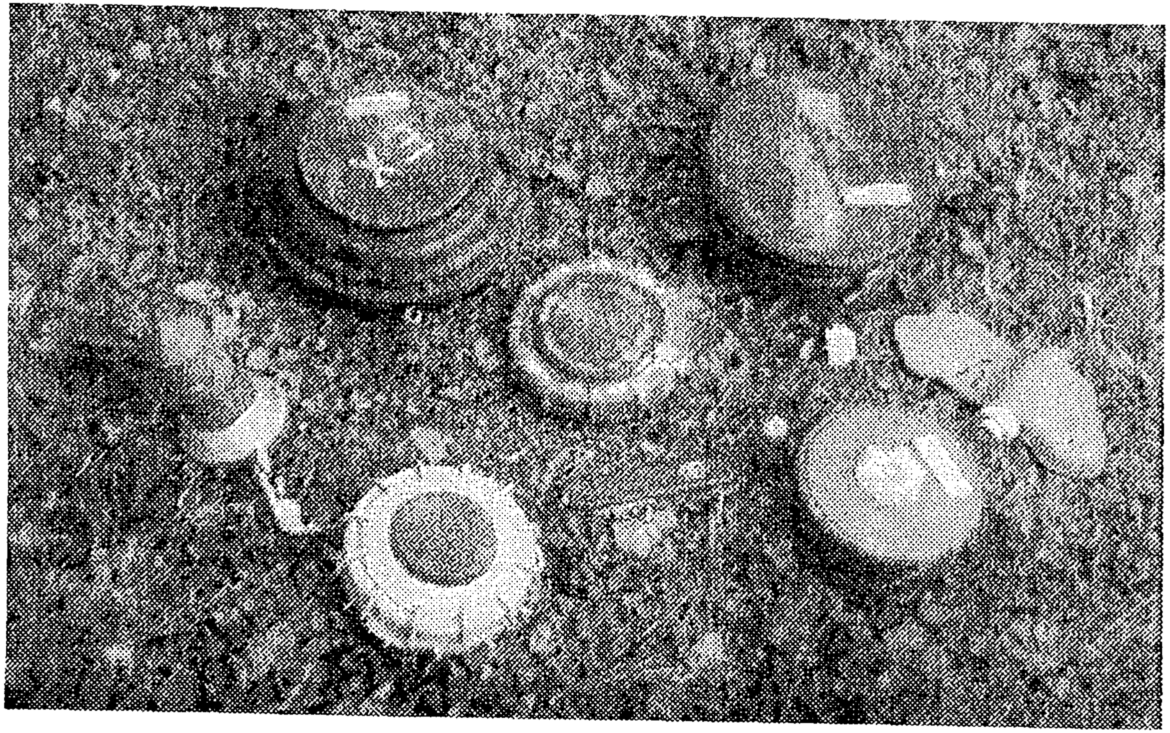
MINEX Dual Frequency Detector Performance

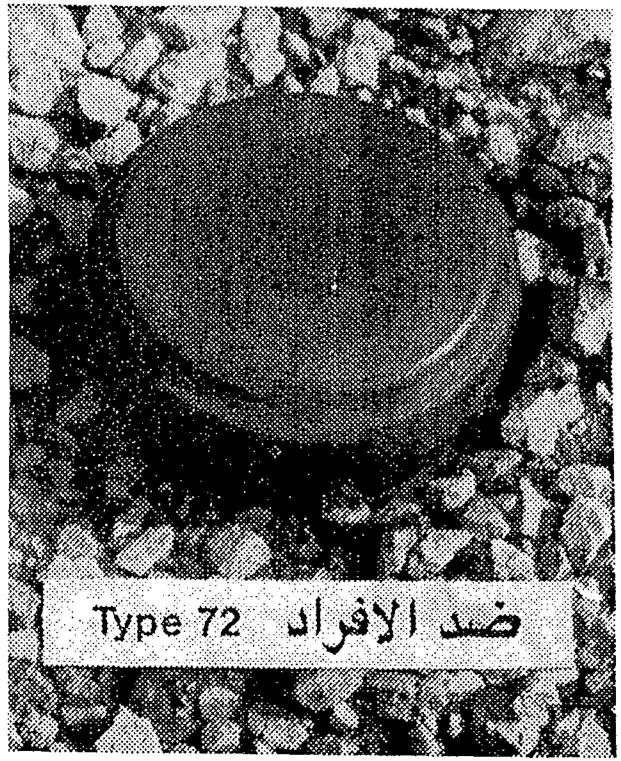


Extreme sensitivity and excellent pinpointing of smallest metal parts including stainless steel, target-selectivity and -resolution are the superior features of the MINEX Dual Frequency Detector.

Foerster MINEX 2 FD

Detectable ? → **YES !**

Mine Detector



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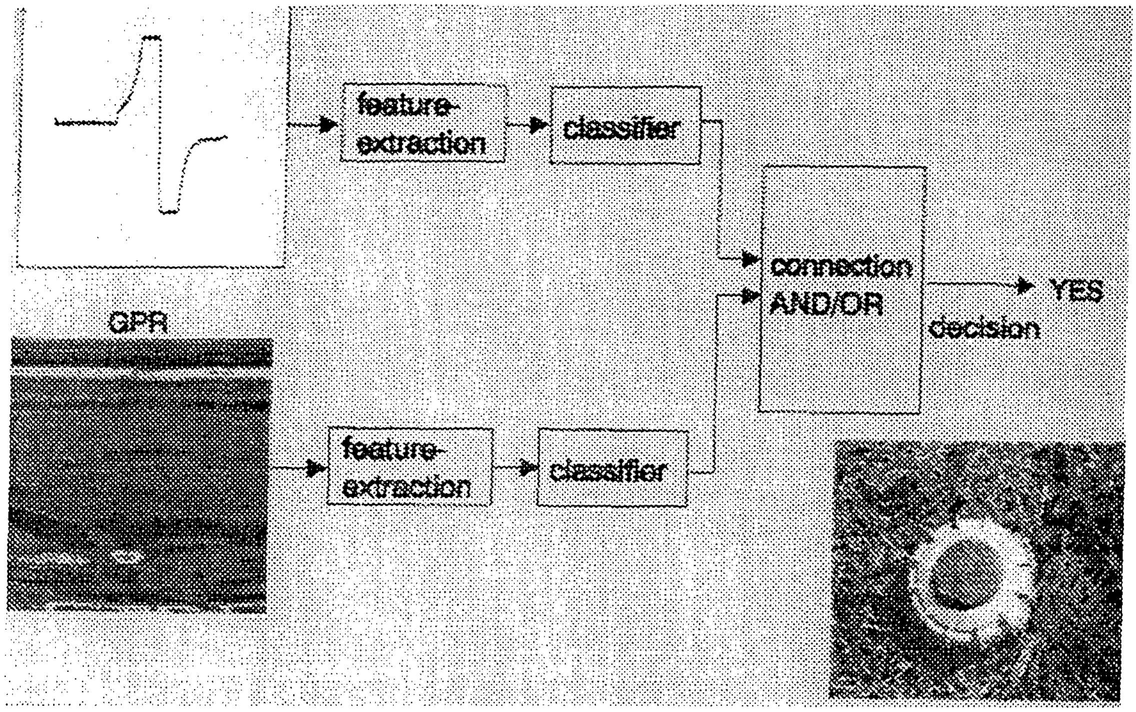
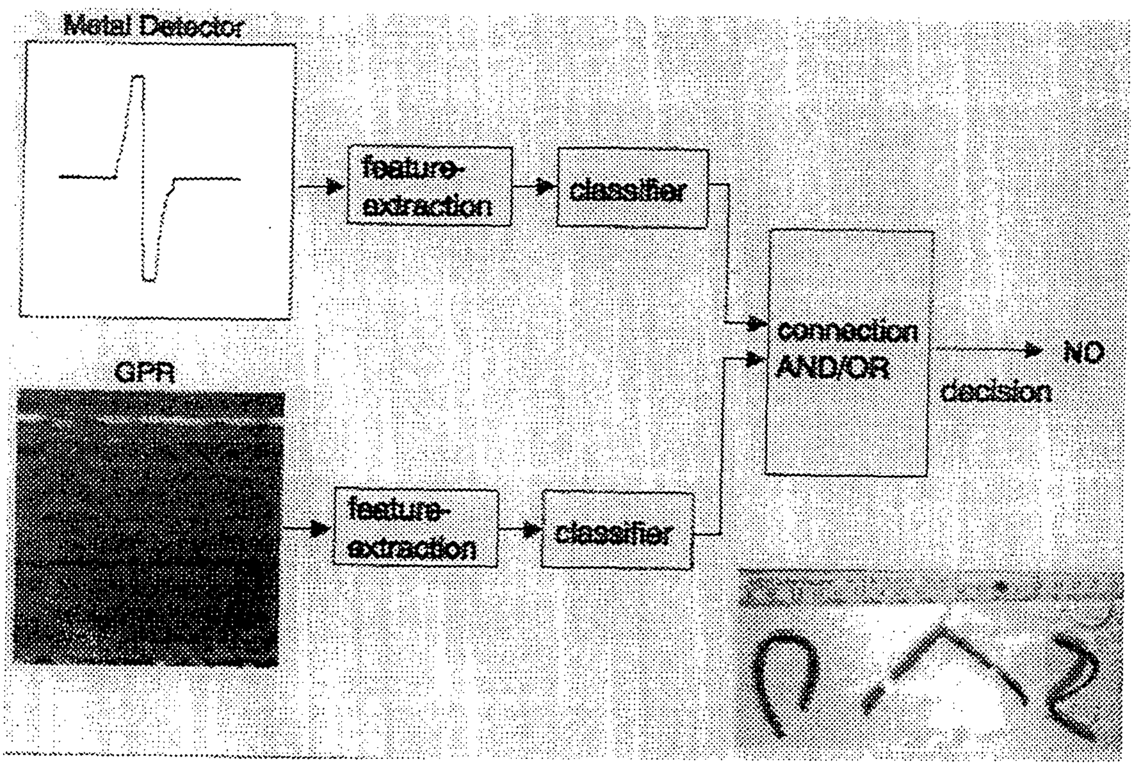
Fusion of GPR- and MINEX-Sensor



For better object indentification and for reducing the false alarm rate a fusion of a GPR- and the MINEX-Sensor has been tested by Daimler Benz A. G. Forschung und Technik, Germany



System Integration for Imaging Detection

For System Integration MINEX Sensors, Signal Evaluation and Processing Electronics are used as "components", linked by cables and mounted on platforms.

These MINEX platforms become part of sensor vehicles and can be combined with FEREX (MK 26) or other type of sensor arrangements.

As a revolutionary novelty the MINEX sensor is used in an orthogonal sensor arrangement (Patent pending) with an identical second receiver coil system on top. This "Double Gradient Sensor Package" is mounted in a rotating scanner with a width of 1 m.

The following two pictures show the principle of operation and of the imaging detection in real time, realized by DORNIER, Germany. The last picture shows the parallel tracks of a real field highly contaminated with ordnance and explosive waste and scanned with the rotating MINEX Sensor System.

ODIS ACTIVE SENSING

Dornier

Induction Coil Sensors

Purpose:

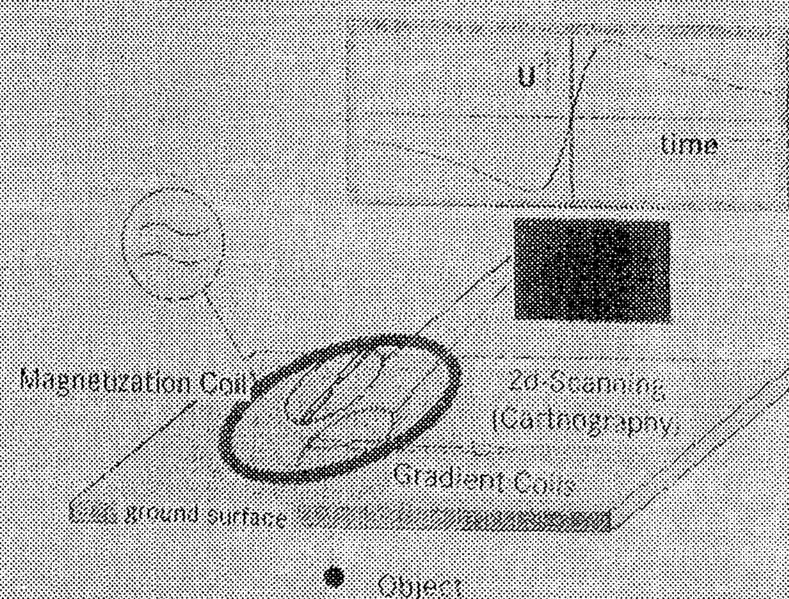
Detection of
near surface (depth <30 cm)
metalic
small
objects

Technique:

Induction Coil Sensing

working with

- 1 Magnetization Coil
- 2 Gradient Coils



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PORTABLE TURNKEY UXO DETECTION SYSTEM
High Quality Data Acquisition→ Accurate Navigation→ Data Analysis

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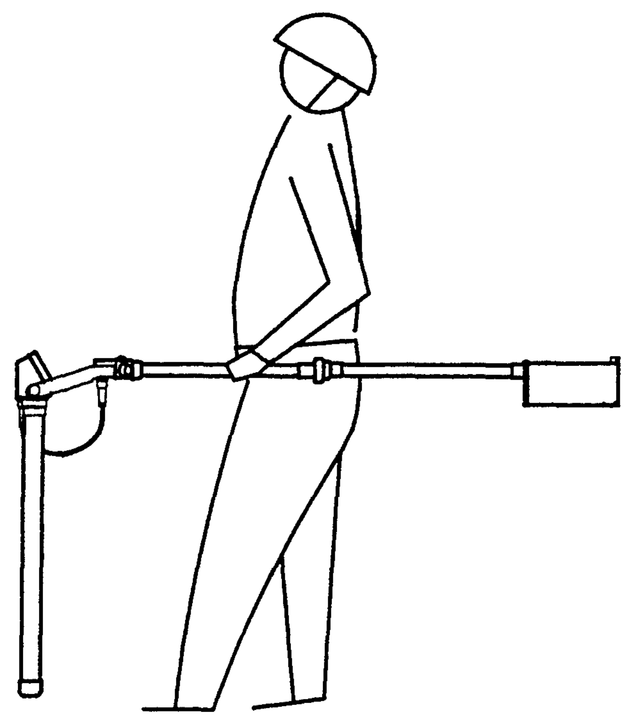
INTRODUCTION

After many years and several generations of product development advancements, the company Vallon GmbH has responded to the market needs of the UXO user community with a fully integrated Man-portable Ordnance Locator. Reality aspects seek user friendly equipment which are cost effective (survey time + reliable data processing), to the OEW operator and provide qualified data which meet Government standards.



Equipped with proven detection technologies along with current survey and software techniques, such a system will work effectively today and into the future. The Vallon Ordnance Locator System has been designed to accept further technical improvements as the needs and components become available.

SYSTEM INTEGRATION

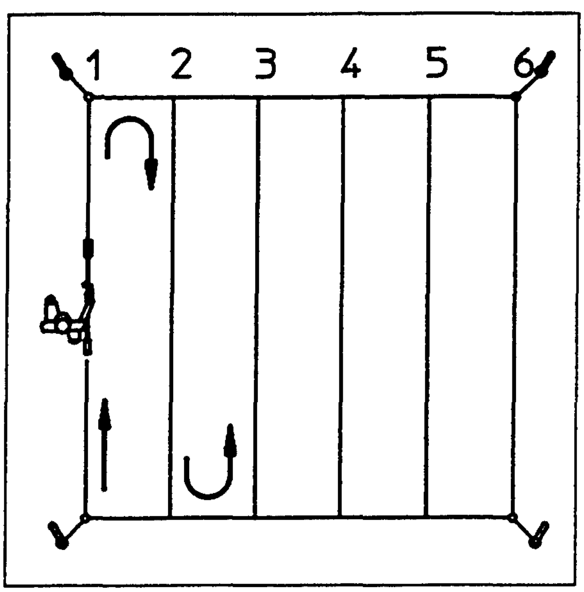
For several decades buried UXO's have been successfully located by means of portable magnetometer instruments (i.e. Cesium and Fluxgate Magnetometers). Specialty expertise has been gained in areas such as Germany from extensive UXO detection requirements since the conclusion of WWII (many UXO's from this period are still detected to date). Fluxgate gradiometers have been proven to be highly accurate. Especially where high concentrations of UXO are found and in urban areas with ambient problematic conditions.

Recently, the value level of Fluxgate Gradiometers produced by Vallon were proven as an effective technology during the UXO Technology Demonstration Program at Jefferson Proving Ground 1994.

An enhanced "Turnkey" UXO detection system has been developed by Vallon based on the experiences and needs of the user community. Both military EOD and OEW companies require a system which is highly portable, versatile in use, easy to operate, and reliable for continuous use in the field.

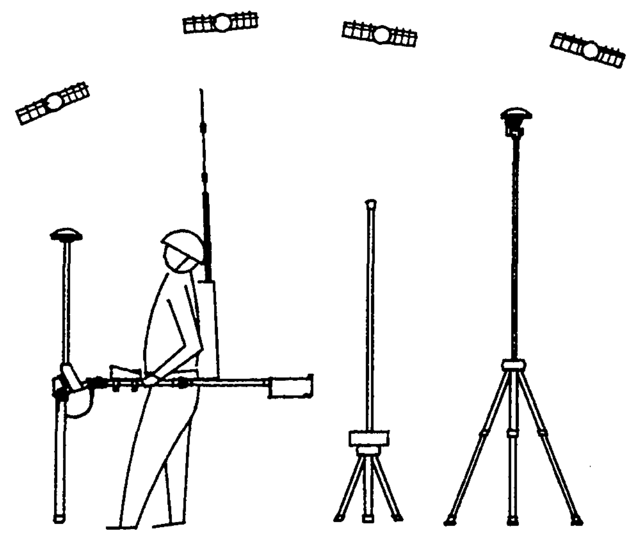
To ensure that these advantages do not get lost when enhanced with "computer-aided detection", it is absolutely necessary to have an exact navigation system for the applied detection sensors. Therefore, Vallon developed two distinct navigation aids for use by the same detection equipment:

A) SEPOS®-Sensor Positioning System (manually operated guiding lines with accuracy markers).



Application:
Narrow roads, narrow valleys, forested areas, and bore holes.

B) DGPS-Differential Global Positioning Satellite (radio link navigation - no guiding ropes required).



Application:
In open areas such as firing ranges where clear satellite links are available.

In both cases the magnetometer data is recorded together with the data of the navigation system. A final target list produced after evaluation comprises the combined data with a target description and target location (the GPS coordinates are easily converted to UTM).

The use of "conventional" UXO detection methods has vastly improved with the turnkey system approach increasing detection performance and detection quality assurance. Current improvements with GPS technology has increased detection location accuracy to a very high level. The results of these combined improvements include:

- The EOD personnel operating the system can fully concentrate on the detection survey.
- The target data collected with GPS values are a reliable reference without the need for physical reference points which could become lost from extreme weather conditions, construction changes, etc.
- Quality assurance can be performed at the data analysis level on a PC. It is not necessary to repeat an area survey.

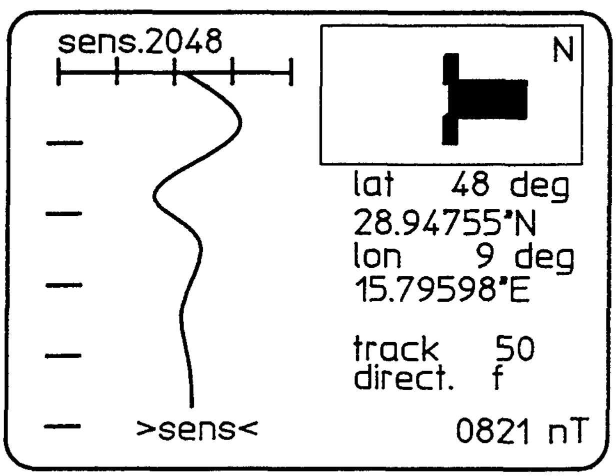
DATA QUALITY REQUIREMENTS

Two considerations are very important to obtain the desired results of high quality detection data:

1. Reliable data acquisition.

2. No change in the "original" measured data during the evaluation.

The reliability of the data survey for UXO's is ensured by the use of a data acquisition unit with graphically displayed information for the operator. With the use of this real time display, the survey can be "quality checked" in the field during the operation. Should an error occur, the localized area of the survey field can be immediately re-surveyed without effecting the overall collected survey data. Thus, quality and reliable data is ensured throughout the survey operation.



Vallon GmbH produces a complete detection system which includes the Micro Computer MC1 for data acquisition. The MC1 displays actual true-to-scale nT values at the present survey location of the magnetometer. At the same time, the last segment recorded survey tracks (5.4 meters), are also on display.

When the GPS option of the MC1 is in operation, the operator now has directional guidelines on the display. This accuracy points the way for each surveyed track to be recorded. MC1 programming ensures that all GPS tracks are in order for correct field coverage and tracks cannot be repeated of left out. This means that the collected values, which are later transferred to a PC for analysis, are absolutely complete and free of errors.

The nT values of buried ferrous objects can be very different depending on the size, magnetic characteristics, position (angle), and influences of other nearby ferrous objects. Therefore, it is necessary that the nT values are recorded genuine and with absolute accuracy. On the MC1 display, an operator will recognize the characteristic features of a ferrous object (UXO).

THE ORIGINAL DATA SHOULD NOT BE CHANGED BY ANY CALCULATION OR MANIPULATION.

Vallon GmbH also produces the signal processing software EVA (Evaluation and Analysis), as an optimum tool for this purpose. "Original data" collected from the MC1 may be displayed on the EVA program in parallel to an "ideal graph" with true scale representation. With this means, the software operator can evaluate the quality of the data and manually influence complicated signal graphs to avoid any misinterpretation by the computer.

On the completion of a data analysis, a final report is produced which includes a target (UXO) list and a true-to-scale target map. Important information is provided on the target list including target location (latitude and longitude when GPS is used), target depth, signal size of target, inclination, etc. The target map provides an excellent visual representation on the levels and locations of contamination.

CONCLUSION

In brief, it is now possible to obtain high quality and reliable data from a UXO field survey operation. Having stored and analyzed target data provides baseline information for the present and future survey of a given site. An integrated "turnkey" system is now field usable and can provide a higher level of quality assurance over past manual operation methods.

PROBING CHEMICAL CONTAMINATION FROM UXO WITH SIMS

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ABSTRACT

Secondary ion mass spectrometry (SIMS) is a surface analysis technique that is applicable to the characterization of areas contaminated with leaking, chemical unexploded ordinance. In SIMS, the sample is bombarded with an energetic particle, which results in contaminant chemicals being "sputtered" into the gas phase, where mass measurement and detection can occur. Instrumental advances have resulted in the development of a massive molecular particle for surface bombardment, management of surface charge on insulating samples, and identification of contaminants from surfaces which represent complex mixtures. Investigations which employ a quadrupole SIMS, and an ion trap SIMS instrument are described. Specific laboratory studies are discussed which describe the analysis of alkylmethylphosphonic acids (CW degradation products), tributyl phosphate (a CW simulant), and organosulfonium ions (CW degradation products). Technology development is expected to result in the fabrication of small scale ion trap SIMS instruments which may be deployable in the field.

INTRODUCTION

On the shores of a lake, nearly every child (and many adults), will stoop, select a stone, and throw it out over the water. The stone strikes the water, and many drops and droplets will be lifted off the surface of the water, into the air. This simple picture forms a useful way to envision an emerging technology called static secondary ion mass spectrometry (SIMS), which is finding application in the detection of chemical warfare (CW) residues on environmental and industrial surfaces. When a sample is characterized using SIMS, the surface of the sample is bombarded by high energy particles (Figure 1). The impact of the particles causes molecular disruption of the surface, which results in contaminant chemicals being lifted from the surface. Once freed from the surface, the chemicals can be readily analyzed. Sample characterization using SIMS is appealing for a number of important reasons:

1) many CW residues are surfacting, or surface active, by nature, and hence prefer to reside on sample surfaces;
2) operationally, SIMS is easy to do. No wet chemical extraction or manipulation is necessary;
3) improvements in instrumentation have resulted in enhanced chemical sensitivity and selectivity;
4) the technique offers the promise of small instrumental size, and hence the possibility for transportability and field application.

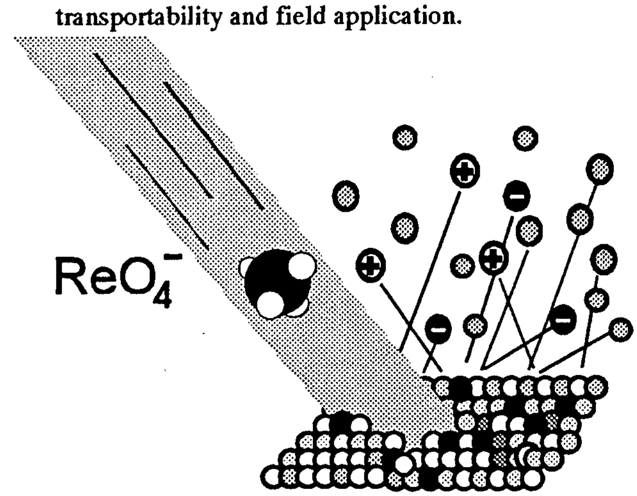

Figure 1. Schematic diagram of an energetic particle striking a sample surface. "Secondary" ions, which are diagnostic for the contaminant chemical, are "sputtered" into the gas phase above the sample surface.

In this report, the fundamentals of SIMS analysis will be described, and contrasted with conventional analysis. Potential application scenarios will be identified, and the status of technology development will be outlined. Finally, brief accounts of the application of SIMS to the detection of CW residues will be presented.

SIMS: PRINCIPLES AND TECHNOLOGY

SIMS is most directly applicable to the characterization of solid samples, such as soil, paint chips, rubber gaskets, and charcoal. The sample is prepared for analysis by sticking it to a sample holder using double sided tape, and then attaching the sample holder to a steel probe (Figure 2). Using the probe, the sample is placed inside the vacuum chamber of the SIMS spectrometer, where the pressure is 10^{-3} to 10^{-6} torr. Under these vacuum conditions, volatile chemicals will evaporate, and will not be detected using SIMS. However, less volatile

chemicals, which are typical of CW residues, will not evaporate, and may be detected.

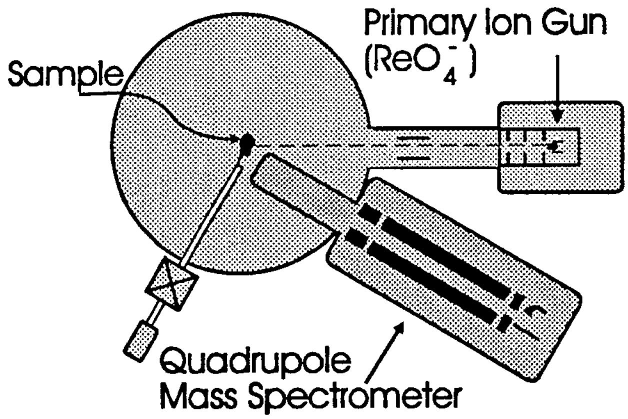

Figure 2. SIMS instrument which utilizes a quadrupole for mass detection.

Once in the vacuum system, the sample surface is bombarded with energetic, charged particles called ions. In *static* SIMS, the total number of bombarding particles is kept small, such that any given area on the sample target has been struck only once. This limitation ensures that the sample is not unduly changed by the particle bombardment.

Three advances in SIMS instrumentation have dramatically improved its application to characterization of environmental samples: *pulsed extraction*, the *perrhenate primary particle*, and the *ion trap SIMS instrument*. Pulsed secondary ion extraction greatly improved the analysis of environmental samples, because it solved a problem which arose from the buildup of electrical charge which occurs when electrically insulating samples are bombarded with energetic particles. This was particularly troublesome because most environmental samples (e.g. minerals, vegetation) are insulating. Pulsed extraction neutralized the charge buildup by alternately extracting positive, then negative ions from the sample (Appelhans, 1990). This also resulted in the simultaneous collection of the positive and negative SIMS spectra, which was beneficial because both polarity are needed for CW applications.

Improved "sputtering" of surface contaminants was achieved by employing the perrhenate ion (ReO_4^-) as the bombarding particle. Using again the "stone in the lake" metaphor discussed above, the perrhenate particle is analogous to throwing a large, flat rock: it does not immediately go to a great depth, causes a lot of surface disruption, and launches a great deal of water into the air. On the surface of a sample, perrhenate acts in this fashion, because it is a *molecule*, and it is heavier compared to the atomic particles that are in conventional use (Delmore, 1995). Perrhenate (five atoms, 250 atomic mass units (amu)) was 10 times more effective at sputtering molecules from salt samples, when compared with gallium (one atom, 70 amu).

Many of the detection applications cited in this paper were performed using a *quadrupole* SIMS instrument (Figure 2). The quadrupole SIMS is more mature technology, and functions as a "work horse" instrument in the laboratory. It is reliable, and easy to operate: non-degreed technicians have been trained to make measurements using this instrument. The drawbacks to the quadrupole SIMS are that no collisional stabilization occurs in it, and it cannot be used for MS/MS (see below). Because of these limitations, we believe the ion trap SIMS, even though it is a more complex instrument at this time, is the best mass spectrometer for detection of compounds on environmental samples.

The combination of an *ion trap* mass spectrometer with SIMS technology has resulted in instrumentation which is capable of improved observation of sputtered contaminant ions (Figure 3). This occurs because they

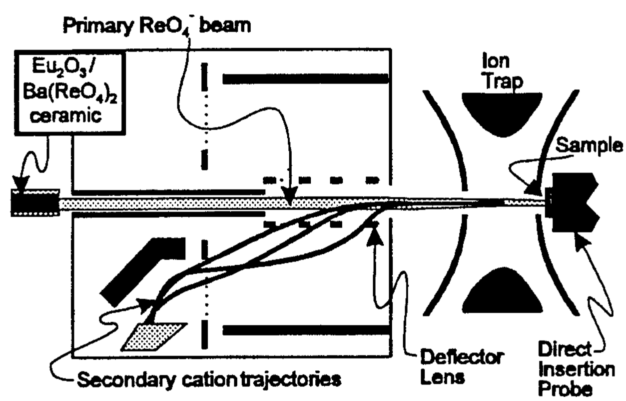

Figure 3. Ion trap SIMS instrument.

are collisionally cooled in a bath gas of Helium, which is present inside the ion trap (Broadbelt, 1995). The He pressure inside the ion trap is 3 - 4 orders of magnitude greater than the pressure in the target region of the quadrupole. The ion trap also is capable of mass spectrometry/mass spectrometry (MS/MS), which is invaluable for identifying contaminant chemicals in the presence of endogenous chemicals typical of most environmental samples. To perform MS/MS, only ions of the mass of interest are stored in the ion trap; other ions are ejected. The stored ions are then excited, and

the excitation causes them to fragment. The masses of the fragment ions are diagnostic for identification of the contaminant chemical. Ion trap SIMS instruments are also attractive because they are small in size, and have the potential for transportability. This expectation is supported by the fact that ion trap mass spectrometers have been used in the field (Wise, 1993).

CHEMICALS AND SAMPLE TYPES

SIMS can be effectively used for the identification of a variety of contaminant chemicals. Chemical attributes which favor a SIMS detection are:

1. Involatile. Contaminant chemicals which exist primarily in the condensed phases can frequently be detected. An example is chlorovinylarsonic acid. In contrast, chemicals which exist primarily as gases (e.g., phosgene) are not amenable to a SIMS detection approach, unless they have reacted with the surface (e.g., TBP).
2. Surfacing tendency. Contaminant chemicals which tend to reside on the surface are usually easily observed using SIMS. Relevant examples are the alkyl methyl phosphonic acids (AMPAs), which have an ionic "head" (the oxyphosphorus acid), and a hydrophobic "tail" (the hydrocarbon alkyl group).
3. Readily ionized. Contaminant chemicals must have an easy ionization mechanism for SIMS detection, *preferably by a Bronsted acid/base process* (i.e., addition, or removal of H^+). The AMPA chemicals are good examples of this attribute also: they readily form (indeed primarily exist as) [AMPA - H]$^-$ ions. In contrast, nitro-compounds (e.g., explosives) are not easily ionized in SIMS, and have not been easily detected to date.

SIMS can be used to investigate the surface of a wide variety of *solid* sample types. Soil, rock, gaskets, paint chips, leaves, fibers, filters, salts, charcoal, and metals can all be effectively analyzed using SIMS. For these types of solid samples, SIMS detection is more difficult when the target chemical is *absorbed into* the sample (as opposed to *adsorbed onto it*). Water samples can also be analyzed, by taking a small sample (50 to 100 microliters) and evaporating it onto a metal sample holder. Gaseous samples cannot be analyzed using SIMS, unless the target chemicals adsorb onto solid surfaces. For many chemicals this does, in fact, occur: an example is cyclohexylamine, which will readily adsorb onto mineral surfaces, and is easily detected using SIMS (Groenewold, 1996). It should also be stated that those samples which emit lots of gas will present difficulty in the vacuum chamber of the SIMS instrument.

Since SIMS is a surface analysis technique, the spectral response depends on the surface concentration, instead of the bulk concentration. For this reason, SIMS characterization of particulate samples is affected by the surface area: detection will be most sensitive (require the least *absolute* mass of chemical) for those samples which have a lower surface area (e.g., sand, 2 - 3 m^2/g), and will be least sensitive for samples which have a high surface area (e.g., powder, 200 m^2/g).

COMPARISON WITH CONVENTIONAL ANALYSES

A contrast drawn between a surface detection and conventional characterization strategy is useful for understanding the advantages and disadvantages of a SIMS approach. The standard analytical scheme for most organic analytes is separation by chemical extraction, followed by detection. Extractive separation is usually based upon the fact that many target analytes are of low polarity, and are hydrophobic. This has two consequences: 1) the analytes can be extracted from environmental samples using low polarity, hydrophobic solvents, which can be easily removed by evaporation; 2) the analytes can be readily detected using instruments which rely upon the target analyte being in the gas phase. The gas chromatograph is an example of this type of instrument. It must be emphasized that this strategy is effective for a large number of target analytes present at very low concentrations.

However not all analytes are susceptible to an extraction strategy: many significant compounds are very hydrophilic, and are not amenable to extraction. These compounds also have low volatility, which confounds detection approaches which require them to be transported into the gas phase. The hydrolysis products of many pesticides are representative of this type of analyte: hydrolysis increases hydrophilicity, and makes extraction GC analysis more difficult. For this reason, liquid chromatography has been successfully employed for the analysis of many hydrolysis products.
These strategies offer a sharp contrast with analyses using SIMS. Some of the salient differences are presented in Table 1.

Table 1. Comparison of Attributes of SIMS and Extractive Analysis		
	SIMS	**Extractive Analysis**
Compound	low volatile, high polarity, easily ionized	volatile or semivolatile, low polarity, not ionized
Interaction with sample	adsorption to surface	adsorption or absorption
Sample prep	double stick tape to sample holder	wet chemical extraction, concentration, chromatography
Type of samples	solids (1 - 10 mg), evaporated water (10 - 100 μl)	solid (10 g), water (1 liter), air
Analysis time	10 min	hours

APPLICATION OF SIMS TO UXO SCENARIOS

SIMS is applicable to scenarios where *chemical* unexploded ordinance (UXO) is present, and leakage is suspected. In this scenario, a small quantity of soil (as little as one milligram) could be analyzed for the presence of agent, or, more probably, primary degradation products. The ability to make this determination is critical to the safe and efficient disposal of UXO. Since SIMS has been demonstrated for the detection of AMPAs, it is especially well suited for characterizing weapons leaking nerve agent; however, SIMS can also detect leaked blister agent. In a similar fashion, SIMS has utility for characterization of leaked chemical agent identification sets (CAIS).

SIMS may also have application to stockpile decontamination and decommissioning activities. Facilities where chemical materiel was produced and stored have the potential for substantial surface contamination. Selective swipe technology used in tandem with SIMS might be very effective at characterizing contaminated surfaces.

CHARACTERIZATION OF AMPAs ON SOIL

Alkyl methyl phosphonic acids (AMPAs) are significant analytes because they are the primary degradation products of well known nerve agents GB, GD, and VX (Yang, 1992, and Trapp, 1985). In the environment, these compounds all undergo hydrolysis reactions to produce AMPAs (Figure 4). The lifetimes of the hydrolysis products in the environment can be long: the half-life for pinacolylmethylphosphonic acid (PMPA) in the environment has been estimated at 27 years (Kingery, 1995). For this reason, AMPAs are good indicators of environmental problems associated with leaking munitions. Because of the significance of AMPAs, a study was undertaken to determine if they could be observed using SIMS (Ingram, 1995).

When AMPAs are analyzed on environmental samples like soil, a diagnostic spectral "fingerprint" is produced. Since the compounds are acids, the *ions* that are observed are derived from the conjugate base, which arises via the loss of a proton. In addition to the conjugate base itself, fragment ions are also observed, which originate from the decomposition of the conjugate base. A typical SIMS spectrum of PMPA on soil is presented in Figure 5, and the origin of the important ions is given in Figure 6.

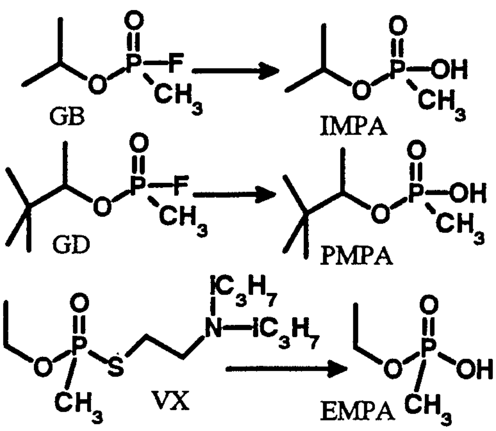

Figure 4. Principle hydrolysis reactions of nerve agents in the environment. IMPA, PMPA, and EMPA are the isopropyl, pinacolyl, and ethyl derivatives of methyl phosphonic acid.

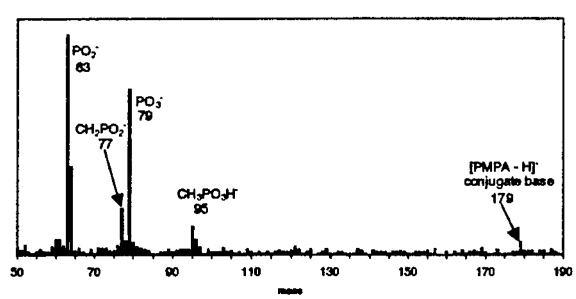

Figure 5. Typical anion SIMS spectrum of PMPA on soil, acquired using a quadrupole SIMS.

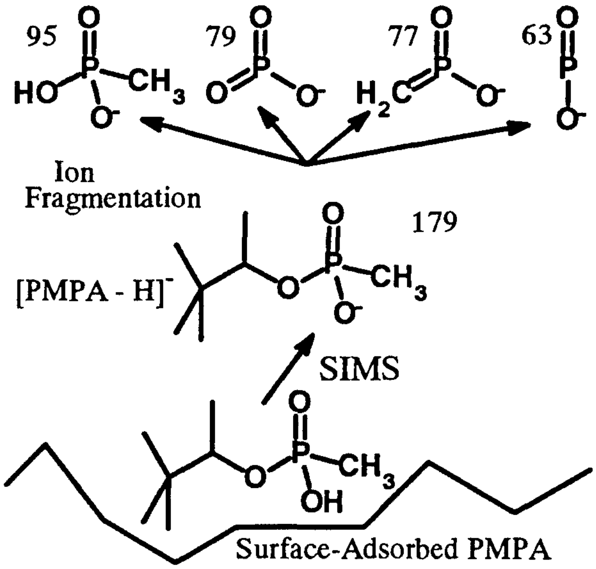

Figure 6. Chemical origin of the spectral signature of adsorbed PMPA acquired using SIMS.

While the SIMS spectral signature of the AMPAs could be readily acquired for most samples, the detection of low concentrations was hindered by the presence of background ion signal. The background can be observed as low abundance ions which occur at nearly every mass (Figure 5). The background originates from adventitious chemicals, which are primarily organic, and which adsorb to most surfaces. This phenomenon manifests itself as a low abundance ion at every mass in the SIMS spectrum, and is one of the consequences of the fact that no chemical separations are performed prior to the SIMS analysis.

In order to measure lower quantities of PMPA, an ion trap SIMS spectrometer was employed. This instrument is capable of stabilizing more of the [PMPA - H]$^-$, which is important because it is the most diagnostic ion. The ion trap SIMS is also capable of performing mass spectrometry / mass spectrometry (MS/MS), which can unequivocally identify the contaminant chemical of choice. The analysis of PMPA can be used to describe the SIMS MS/MS experiment:

1. The sample is bombarded, and [PMPA - H]$^-$ (*m/z* 179) is trapped in the ion trap, along with all other ions.
2. With the exception of [PMPA - H]$^-$, all ions in the trap are excited so that they exit the trap, leaving only [PMPA - H]$^-$.
3. [PMPA - H]$^-$ is excited, so that the ion undergoes fragmentation, but does not leave the trap.
4. Diagnostic fragment ions (95, 79, 63) are detected, thus allowing *m/z* 179 to be identified as originating from PMPA.

MS/MS allows much lower levels of contaminants to be detected, because it enables the analyst to distinguish contaminant-derived ions from those which arise from background. This ability was demonstrated unequivocally in the analysis of tri-*n*-butyl phosphate on soil.

MEASUREMENT OF TBP ON SOIL

Tri-*n*-butyl phosphate (TBP) has served as a CW surrogate, and is also significant because it is used extensively as an extractant in the nuclear industry (Schulz, 1984). Initial analyses of TBP on mineral surfaces, acquired using the quadrupole SIMS instrument, showed that a significant positive ion spectral signature could be easily obtained (Figure 7). However, the biggest ion in the SIMS spectrum was *m/z* 99, which arose by the fragmentation of the protonated molecule (*m/z* 267, Figure 8) (Groenewold, 1995).

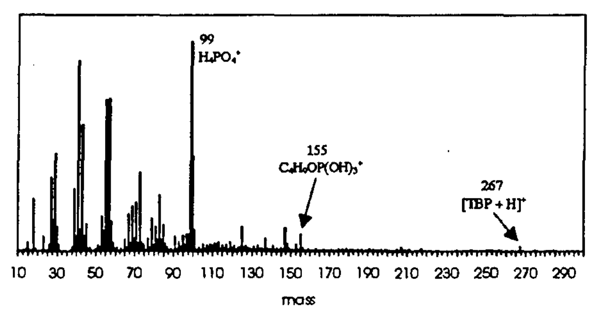

Figure 7. Positive ion SIMS spectrum of TBP on soil, acquired using the quadrupole SIMS instrument.

As in the case of PMPA, detection of small quantities was difficult using the quadrupole SIMS instrument, because the abundance of the protonated molecule was low, and the largest ion shares a mass (99) with other surface contaminants. Thus an ion signal at *m/z* 99 cannot be unequivocally ascribed to the contaminant.

When the contaminated soil samples were analyzed using the ion trap SIMS, the abundance of the protonated molecule (*m/z* 267) was significantly greater than what was seen in the quadrupole instrument. However, the background ion signal was also larger, which (as in the case of PMPA) confounded unequivocal detection. The MS/MS capability of the ion trap was used to identify TBP at lower levels: the 267 ion was isolated in the trap,

and then excited, whereupon fragment ions were observed at 211, 155 and 99.

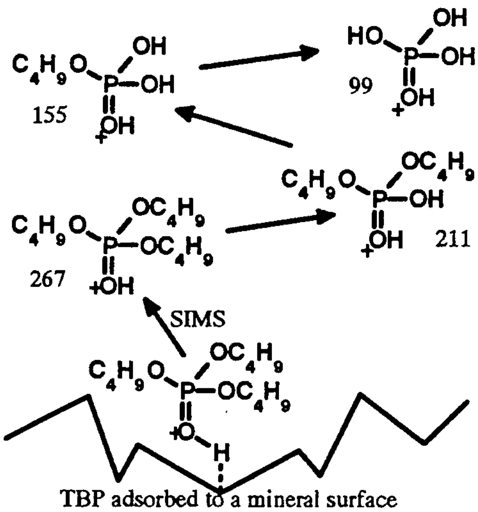

Figure 8. Chemical origin of positive ions observed in the SIMS spectrum of TBP. These ions could be observed in the MS (quadrupole and ion trap) and MS/MS (ion trap) modes of analysis.

To assess the TBP detectability at low concentrations, the abundances of these ions were plotted versus surface coverage (concentration in monolayers, Figure 9). The abundance of 267 decreased with decreasing TBP coverage on the sample surface. But the decrease was small, because the 267 ion signal is actually a composite of TBP, and other background chemicals which are observable independent of the TBP concentration. On the other hand, the fragments of TBP (211 and 155 observed using MS/MS in the ion trap) are very sensitive to the TBP surface coverage. *M/z* 211 was observable at 0.003 monolayers, and the signal was still decreasing at this concentration. For a soil sample having a surface area of 3 m^2/g, this surface concentration corresponds to a bulk concentration of 10 parts per million (mass basis), detected with no sample preparation. Detection of still lower levels of TBP were not undertaken because of complications from TBP contamination present in the laboratory. This result is a dramatic example of the potential of ion trap SIMS for environmental detection of organophosphorus compounds (Ingram, 1996).

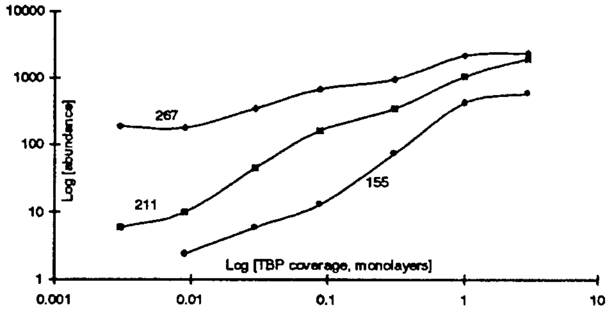

Figure 9. Log/log plot of positive ion abundance versus TBP on the surface expressed as monolayer coverage. Measurements were made using the ion trap SIMS. *M/z* 267 measurements were recorded in the single MS mode. *M/z* 211 and 155 abundances of fragments ions from 267, recorded in the MS/MS mode.

DEGRADATION PRODUCTS OF BLISTER AGENTS

The detection of blister agents (specifically *bis*(2-chloroethyl)sulfide, or HD), and their degradation products, can be challenging as a result of hydrolysis and condensation reactions. These reactions occur after leakage has occurred, and will alter the chemical form of the chemical agent. 2-Chloroethyl ethyl sulfide (CEES), which is a close chemical simulant for HD, was made to undergo degradation reactions to determine if SIMS could be used to detect this type of signature (Groenewold, 1995).

The reactions described below for CEES are practically identical to those of HD (Yang, 1992). In the presence of water, CEES eliminates Cl^- to form a reactive thiiranium ion. This ion will then react with CEES-derived molecules to form high mass sulfonium ions at *m/z* 213/215, and 195 (Figure 10). These ions could be detected on soil that had been exposed to an aqueous solution of CEES (Figure 11). When the same sample was extracted and then analyzed using gas chromatography / mass spectrometry, no evidence for CEES was obtained. This is an excellent example of a sample where contamination would not be detected using conventional methods, but would be readily identified using SIMS.

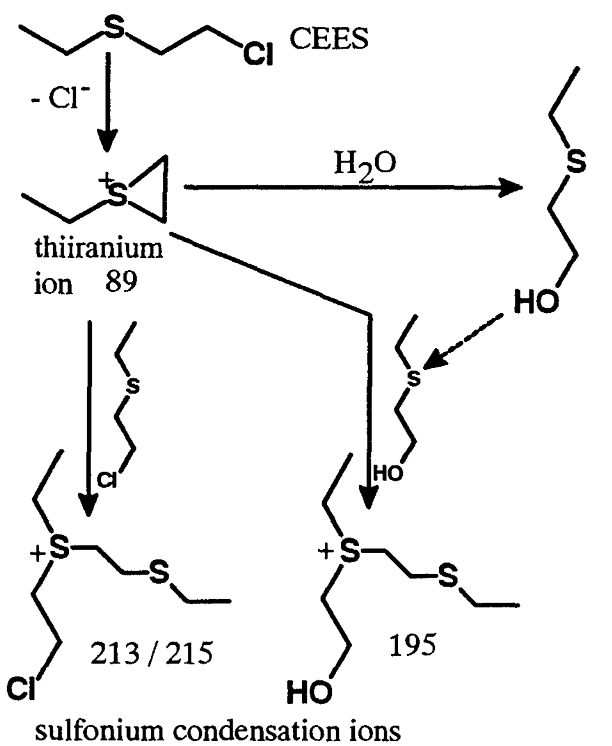

Figure 10. Formation of sulfonium condensation ions, which occurs in solution when the HD surrogate CEES is exposed to water.

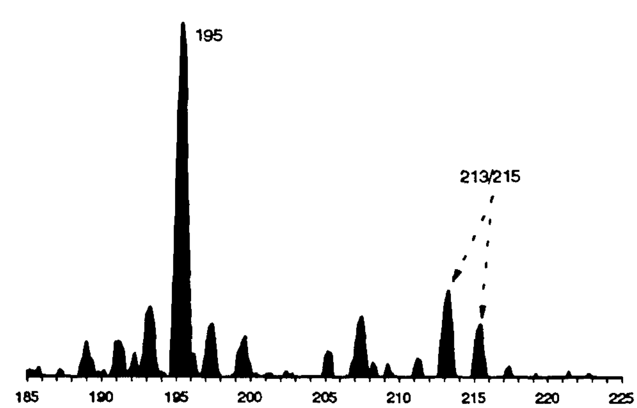

Figure 11. Partial positive SIMS spectrum of CEES degradation products on soil. Spectrum was acquired using the quadrupole SIMS.

The sulfonium ions can also be observed using the ion trap SIMS in the MS/MS mode. The single stage SIMS spectrum shows only a low abundance ion at *m/z* 195, which cannot be distinguished from the background. However, the low abundance 195 can be identified as being derived from CEES by MS/MS, which shows that the ion fragments to form *m/z* 89, the thiiranium ion.

This highlights yet again the analytical enhancement that can be realized using the ion trap SIMS.

FUTURE DEVELOPMENT

The demonstrations of SIMS detections presented in this paper have led to the expectation that a variety of analytical problems associated with leaking, chemical unexploded ordinance can be solved using SIMS. SIMS has been shown to be particularly applicable to the detection of surfacting, ionic species which are typical of CW degradation in the environment. The development of the ion trap SIMS, with its selective ion storage and MS/MS capability, has lowered the detection limits achievable using SIMS, to the 10^{-3} monolayer regime, and further technology improvements may push detection limits even lower. It is emphasized that the SIMS analyses described in this paper were performed in about 10 minutes, without any sample preparation, or waste generation.

These accomplishments have motivated an effort to test the SIMS instrumentation in surety and field environments. Pursuant to this effort, an ion trap SIMS instrument is scheduled for fabrication in FY'96-97, with the goal of testing the response of the instrument to actual agent in a surety facility. If this round of testing is satisfactory, then a second prototype instrument will be fabricated for installation in the Mobile Munitions Assessment System (MMAS). This system will field test SIMS instrumentation for characterization of contaminated samples.

ACKNOWLEDGMENT

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SAR PROCESSING OF GROUND PENETRATING RADAR DATA FOR BURIED UXO DETECTION: RESULTS FROM SURFACE-BASED AND AIRBORNE PLATFORMS

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ABSTRACT

Battelle and The Ohio State University ElectroScience Laboratory (ESL) have built and demonstrated two Ground Penetrating Radar systems for locating buried unexploded ordnance. One system is ground based, towed by an autonomously-controlled vehicle as part of the Subsurface Ordnance Characterization System (SOCS). The other system is airborne, with the radar mounted on a Blackhawk helicopter provided by the U.S. Army Aviation Technical Test Center. The ground-based system has been demonstrated at test areas at Tyndall Air Force Base and Jefferson Proving Ground. The airborne system has been demonstrated at Tyndall Air Force Base. Radar data from surfaced-based GPR demonstrations have been processed using Synthetic Aperture Radar (SAR) processing and images have been created indicating the locations of potential buried ordnance. This work was funded by the Naval Explosive Ordnance Disposal Technology Division.

INTRODUCTION

Battelle and The Ohio State University ElectroScience Laboratory (ESL) have built and demonstrated two Ground Penetrating Radar (GPR) systems for locating buried UXO (Unexploded Ordnance). The goal of both programs was to locate and identify buried ordnance at military sites and allow large parcels of land to be processed. In addition to detection, demonstrated technologies must be able to reliably discriminate between UXO items, shrapnel, and other natural and man-made objects that are not of interest. One system is ground based, towed by an autonomously-controlled vehicle as part of the Subsurface Ordnance Characterization System (SOCS). The other system is airborne, with the radar mounted on a Blackhawk helicopter provided by the U.S. Army Aviation Technical Test Center. The ground-based system has been demonstrated at test areas at Tyndall Air Force Base and Jefferson Proving Ground (JPG). The airborne system has been demonstrated at Tyndall Air Force Base. Radar data from the SOCS GPR has been processed and will be presented. Synthetic Aperture Radar (SAR) processing was used to create an image of the area of interest indicating the locations of targets. Scientists at ESL have applied a complex natural resonance analysis technique to SAR-detected targets to discriminate between buried UXO and clutter items.

The method being used to process the Airborne GPR data will be presented, however at this time the results of the Airborne GPR system are limited.

SOCS GROUND PENETRATING RADAR

SOCS GPR Description

The ground based GPR is a pulsed radar system. It is mounted on a non-ferrous trailer along with other sensors to apply ground penetrating radar technology to the problem of locating and identifying buried ordnance at military sites. Battelle fabricated a non-ferrous towed-trailer and integrated a commercial GPR system into the SOCS. ESL provided the GPR antenna. Battelle and ESL personnel jointly processed the data. The autonomous towing vehicle was developed by Wright Laboratories personnel at Tyndall, AFB in Florida. The Wright Laboratories group, along with subcontractors, also developed the Simultaneous Data Collection and Processing System (SIDCAPS), which controls the autonomous vehicle and stores all sensor data.

The GPR antenna is mounted on the non-ferrous trailer close to the surface of the ground. The trailer is hitched to the autonomous towing vehicle. The GPR transmits impulses at 50 kHz. The transmitted signal travels through the ground and reflects energy back to the receiving antenna when it encounters discontinuities in the electrical properties of the ground. The GPR response is a series of 256 point, 127.5 ns waveforms. The responses from 256 transmitted impulses are sampled to form each waveform. The data points in each waveform are separated by 0.5 ns. The GPR data is collected as a function of position by making several passes over the volume to be imaged.

SOCS Data Processing

Synthetic aperture radar processing of the time domain GPR data consists of defining the volume to be imaged, collecting time domain GPR data, and constructing the SAR image. The image is constructed by summing, for each voxel in the volume, the data point from each bipolar time waveform that corresponds to the round trip time between the GPR antenna and the voxel.

In order to process the GPR data sets, the position of the GPR antenna is needed as a function of time. The SOCS GPR system records each received waveform along with the system time associated with that waveform. The position of the GPR antenna is determined from the GPR time and the position and heading information supplied by a global positioning system (GPS) on the tow vehicle and sensors on the hitch. The sensors on the hitch detect the pitch, roll and yaw angles of the hitch. The time, position of the GPS antenna, vehicle heading, and the hitch pitch, roll, and yaw are recorded 20 times per second.

The position of the GPS antenna, the vehicle heading, and the hitch roll, pitch and yaw are used to calculate the position of the GPR antenna in UTM coordinates. Interpolation procedures are used to find the GPS antenna position and the hitch orientation at each GPR waveform time. A coordinate transformation is used to calculate the position of the GPR antenna at each GPR waveform time.

SOCS GPR SAR Image Construction

For each waveform of the GPR data and for each voxel in the volume of soil that is being examined, we must determine the round trip time for a signal to travel from the GPR antenna to the voxel and back to the GPR antenna. Once we determine this time, we determine the point in each time waveform that corresponds to a particular voxel. To construct the SAR image, for each voxel, we sum the points in each waveform whose time coordinate corresponds to the round trip time for that voxel.

The raw GPR waveforms include the antenna ringing, reflections from the surface, and a gain slope of 30 dB. The antenna ringing is removed by subtracting an average waveform from each waveform and the gain slope is removed by multiplying each time waveform by a -30 dB gain slope. After removing the antenna ringing and correcting for the gain slope in the raw time domain data, the waveforms can be viewed as a function of time or position and a target will appear as series of arcs. Figure 1 shows an example of the time domain response of the SOCS GPR to a target after we have subtracted the average waveform and removed the 30 dB gain slope. Four passes over the target are shown. The radar is nearest to the target in the second pass, where the response is the strongest.

Before forming the SAR image, the time waveform is shifted in time to place the beginning of the waveform at the surface of the ground. If the GPR antenna does not move significantly while the received signal is sampled, the round trip time is a function of the distance from the radar to the voxel and the velocity of the electromagnetic signal through the soil. The velocity of electromagnetic waves in the soil is v, equal to the speed of light divided by the square root of the dielectric constant of the soil, ϵ_r.

The data from the GPR antenna is in the form $A(m,n)$, where A is an integer array, m is the position or waveform index, and n is the time index within the waveform. m ranges from 0 to the number of waveforms in the data set minus 1. n ranges from 0 to 255, the number of data points in each waveform minus 1.

If d is the one way distance from the GPR antenna at the mth position to the voxel centered at coordinates (x, y, z), the round trip time t for the voxel is

$$t(m,x,y,z) = 2\,\frac{d(m,x,y,z)}{v} \qquad \textbf{(1)}$$

In the mth waveform, the time index of A that contains the data from the voxel at (x,y,z) is

$$n(m,x,y,z) = \frac{t(m,x,y,z)}{\Delta t} \qquad \textbf{(2)}$$

Δt is the time interval between data points in the GPR time domain waveforms. The resulting SAR image is

$$I(x,y,z) = \sum_{m=0}^{M-1} A(\,m,\ n(m,x,y,z)\,)\ e^{2\beta d} \qquad \textbf{(3)}$$

The $e^{2\beta d}$ term is to correct for the attenuation losses due to the soil conductivity, where

$$\beta \approx \frac{\sigma}{2}\,\frac{1}{\sqrt{\epsilon_r}}\,\sqrt{\frac{\mu_0}{\epsilon_0}}\,. \qquad \textbf{(4)}$$

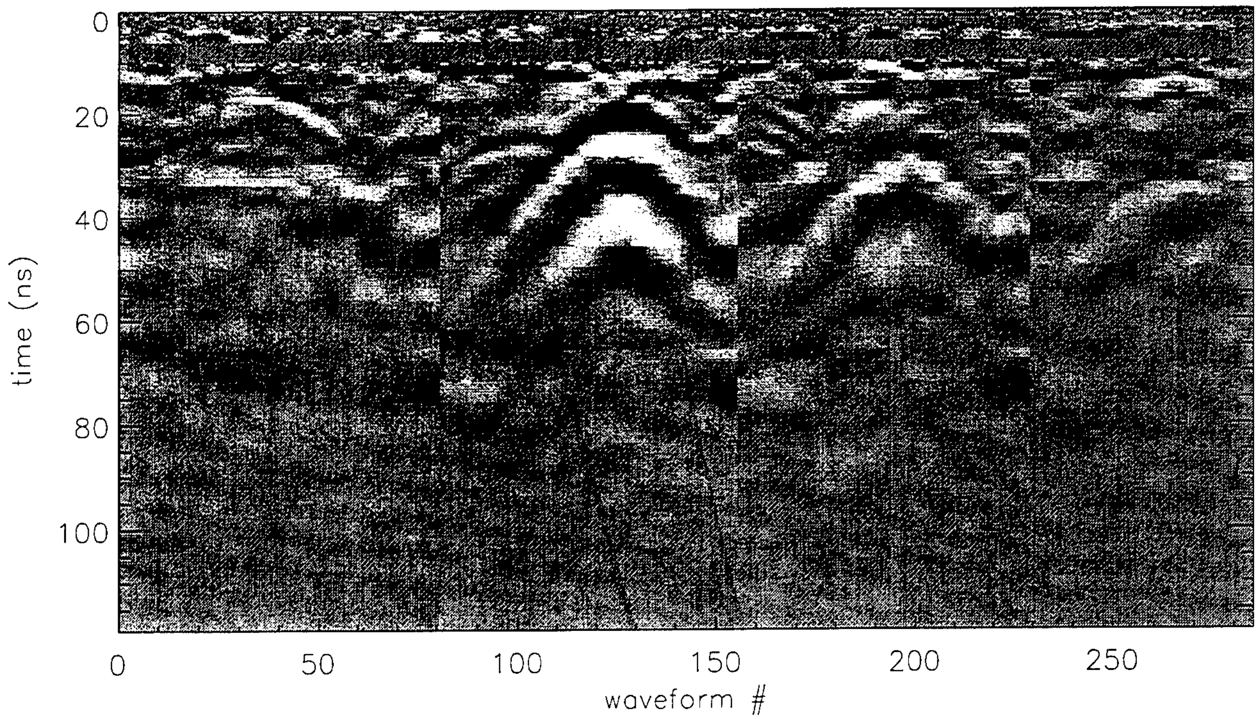

Figure 1 Time Domain Response of SOCS GPR.

σ is the soil conductivity. In the SOCS GPR data processed so far, we have ignored the effects of the soil conductivity when constructing the image.

In general the velocity in the soil may not be constant. The velocity may be a function of depth in the soil. Measurements of the dielectric constant and conductivity of the soil at the site at Tyndall Air Force Base indicate that the dielectric is approximately constant all depths with which the GPR is concerned. However, at JPG the measured dielectric constant of the soil is greater than at Tyndall and increases with depth. This complicates the calculation of the propagation time because the changing dielectric constant changes the velocity and also the path of the radar signal. The path becomes curved and the time it takes a signal to travel through the soil increases. The change is taken into account when doing the SAR processing with the following procedure.

If the dielectric constant of the soil is not constant, the propagation velocity in the soil is some function $v(x)$. For a voxel at depth d and angle of incidence θ, geometrical optics can be used to determine the path that connects the radar and a selected voxel. The radial distance r from the radar antenna is given by

$$r(d,\theta) = \int_0^d \sin\theta \frac{v(x)}{\sqrt{v_o^2 - v(x)^2\sin^2\theta}}\, dx \qquad \mathbf{(5)}$$

for $0 \geq \theta < \pi/2$. v_o is the initial velocity in the soil at depth x=0. The two-way propagation time is then,

$$t(r,d) = \int_0^d \frac{v_o}{v(x)\sqrt{v_o^2 - v(x)^2\sin^2\theta}}\, dx \qquad \mathbf{(6)}$$

However, when processing the GPR data, we do not know θ. We know the depth of the voxel, d, and the radial distance between the voxel and the radar, r. We must invert Equation 5 to solve for θ and then substitute θ into Equation 6 to find the two-way propagation time.

If the velocity can be approximated as a linear function of the form,

$$v(x) = v_o - \alpha x \qquad \mathbf{(7)}$$

the integrals in Equations 5 and 6 can be evaluated exactly.

To invert Equation 5, for each voxel depth, we create a vector containing the radial distances, r_i, for the angles $\theta = (\pi/2)\, i/n$, where n=1000. For each depth we have r_i as a function of θ_i. To get θ as a function of r, we use an interpolation procedure which performs a linear interpolation on vectors with an irregular grid. This interpolation procedure gives us

θ_j for the known radial distances r_j, allowing us to calculate the two-way time from Equation 6.

ESL measured the dielectric constant at Jefferson Proving Grounds 6 feet south of marker A24 as a function of depth . The measured dielectric constant and the linear approximation used for the SAR processing are shown in Figure 2.

SOCS GPR Results

Tyndall Results

Four complete GPR data sets were recorded at a test site at Tyndall Air Force Base. Known ordnance items were buried in sand at the test site. The SOCS vehicle drove over the test pad four times, twice driving primarily north-south and twice driving east-west. The parallel passes were approximately 1.5 to 2.0 meters apart. Figure 3 shows the paths followed during the east/west run and the north/south run used to create the SAR images below. We have determined the coordinates and depths of the ordnance using the SAR images. Figure 4 shows the SAR image collapsed to two dimensions. The image shown is the sum of the absolute value of the image at each depth of the image.

Figure 5 the known buried ordnance locations are marked with triangles and the targets found using the GPR SAR image are numbered and marked with Xs. Complex natural resonance (CNR) analysis was used to estimate the lengths of the targets. 18 of the 22 known ordnance items were found, disregarding the 9 closely spaced plates along the southeast edge of the image. A total of 38 potential targets were identified. The CNR analysis revealed that Target #3 and #4 are probably the same target and Target #15 and #16 are the same target. Two resonances were found at the coordinates of Target #30.

Problems with the Tyndall Results

There were several problems encountered during the SOCS GPR Tyndall tests that should be corrected for future tests.

One significant problem effecting the SAR imaging is an error in the recorded GPR antenna coordinates. The vehicle actually moved very smoothly, but the positions recorded by the system are not always evenly spaced. To correct for this, a 30-point running average was used on the coordinates of each trace. This did improve the SAR image, however there is still some possible position error, especially when the vehicle turns.

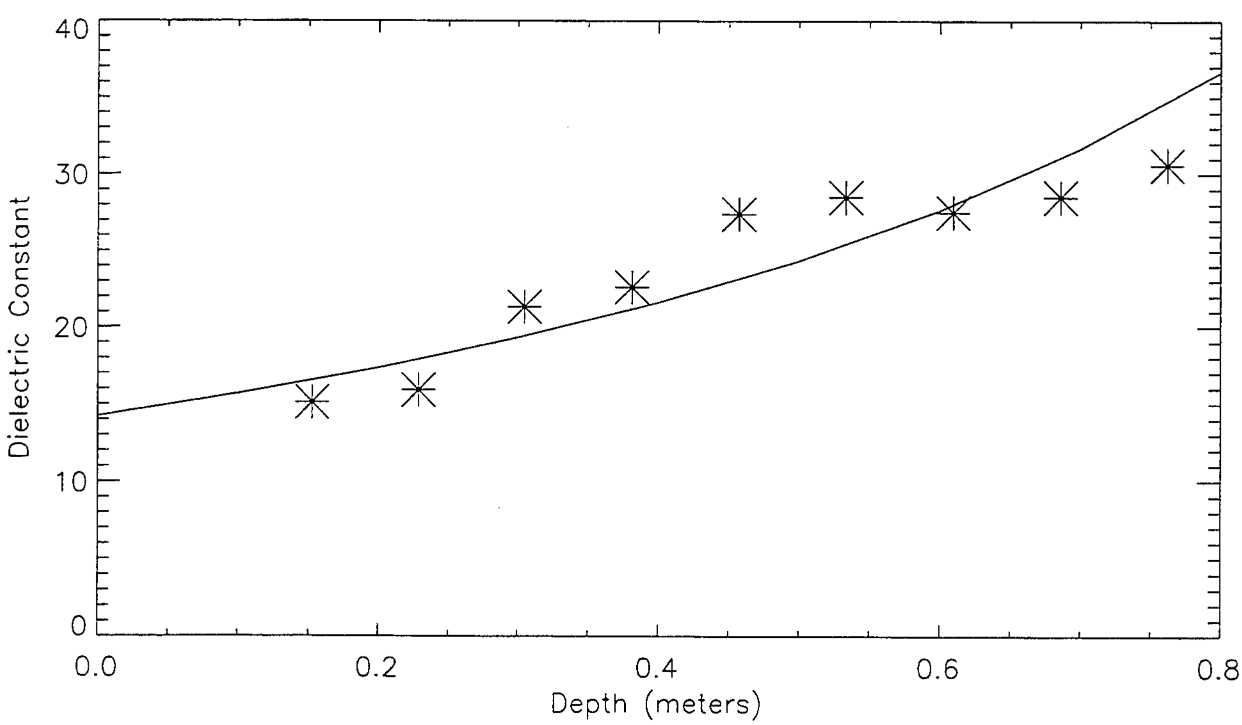

Figure 2 Measured and Approximated Soil Dielectric Constant at JPG.

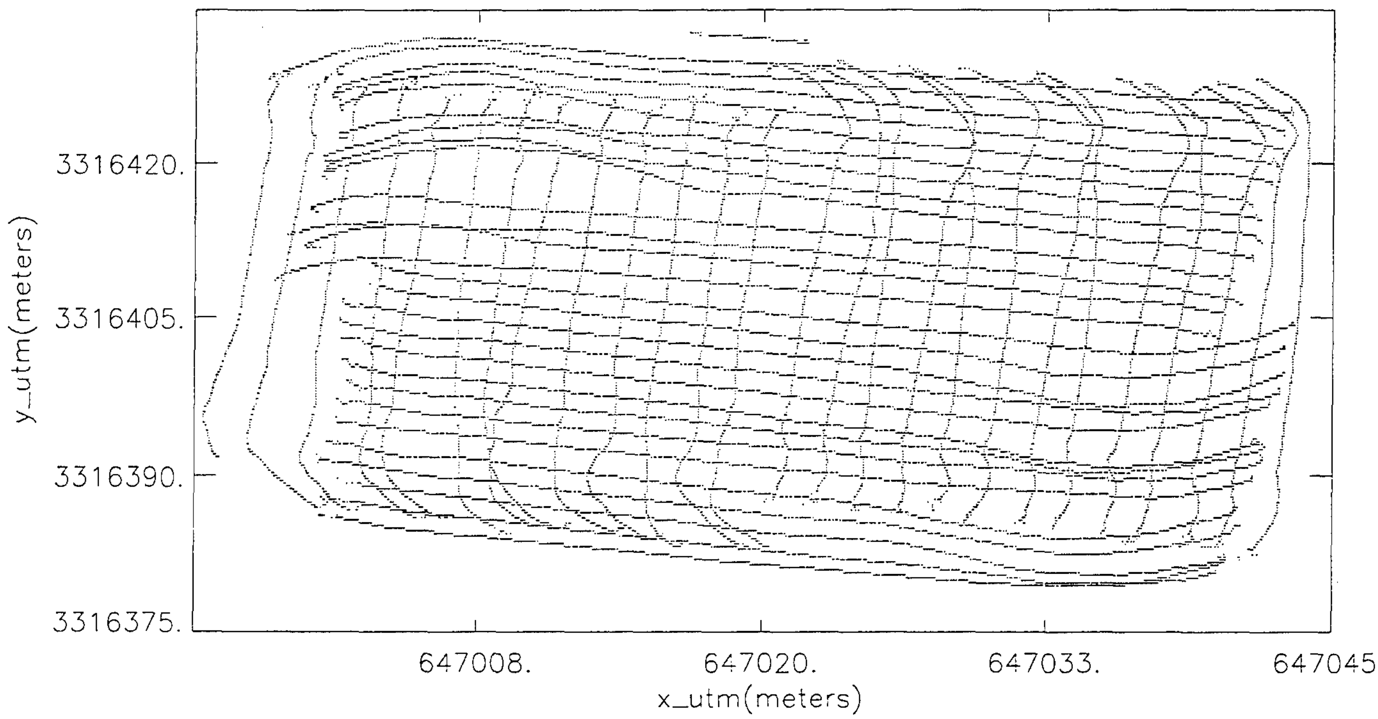

Figure 3 SOCS GPR Path at Tyndall.

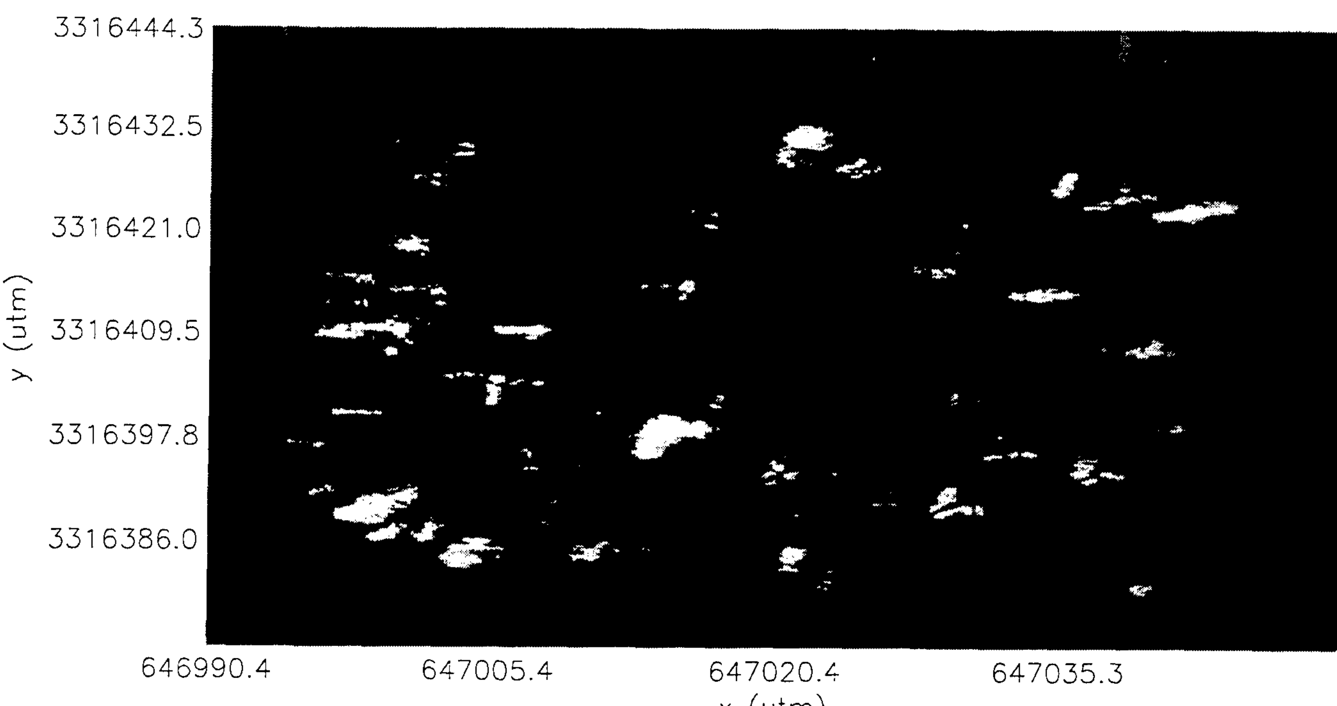

Figure 4 SOCS GPR Tyndall Collapsed SAR Image.

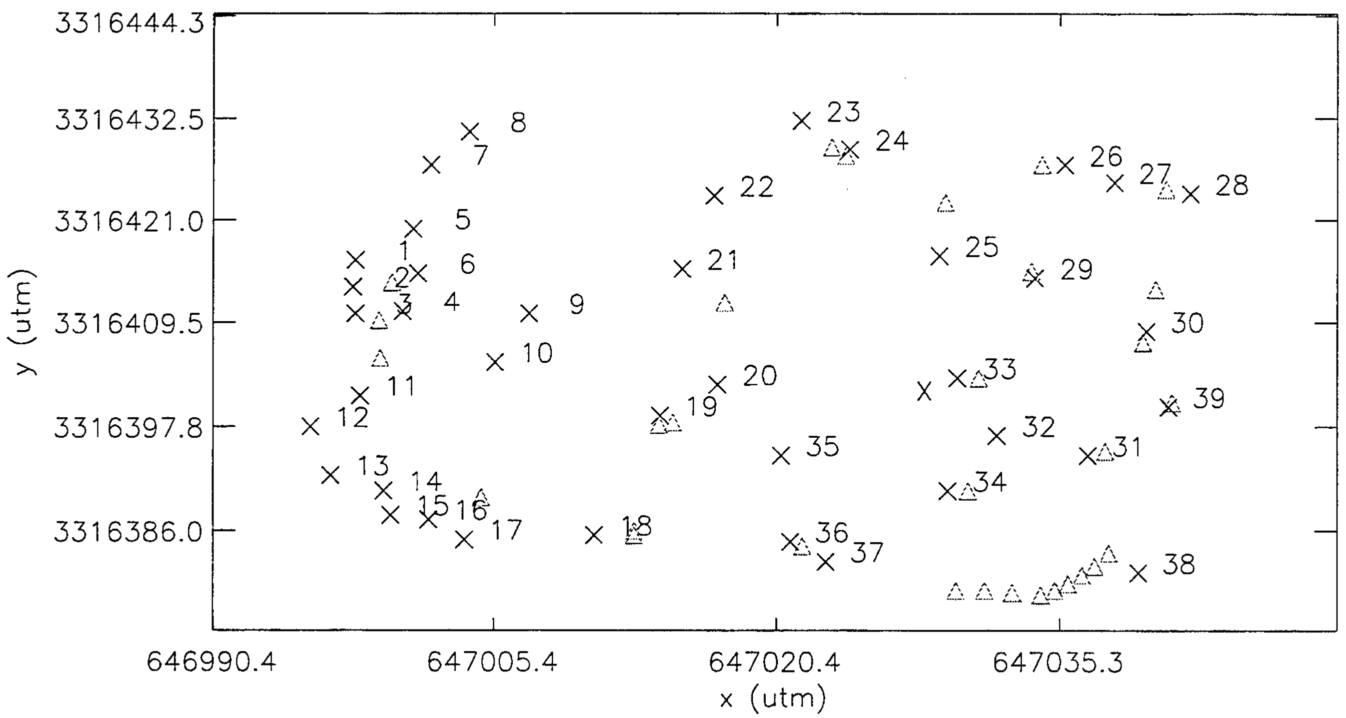

Figure 5 Known Ordnance Buried at Tyndall (triangles) and Targets Found by SOCS GPR (X's).

During all of the SOCS GPR Tyndall tests, the gain on the system was set too high. This resulted in a portion of the time waveform being clipped off. The time waveform was clipped off from 14.5 ns to 17.5 ns (5.75 to 8.75 ns after removing the system offset). Due to the improper gain setting, the arcs in the time domain data corresponding to shallow targets, less than approximately 0.6 meters, are incomplete or distorted, making it difficult to focus the shallow targets at the proper depth in the image. Some of the shallow targets are still detected from the resonant arcs that appear at later times in the time domain data.

The spacial resolution in the direction perpendicular to the path of the vehicle could be increased by making the passes closer together. During the SOCS Tyndall tests, the passes were 1.5 to 2 meters apart and the targets appear unfocused in the direction perpendicular to the path. During the JPG tests the passes are less than a meter apart and the resolution is improved.

JPG Results

Battelle received five GPR data sets from SOCS from the JPG sites. Only one complete data set, C22, contained good GPR data. About one-third of a second data set, D14, was good, but this only consisted of 2 passes on each side of the region. During the remaining runs, the GPR system recorded invalid data for some unknown reason.

The path of the GPR antenna during the C22 run is shown in Figure 6. The parallel passes of the vehicle were designed to be 2.5 feet apart. Figure 7 shows the collapsed image of the C22 data. Several potential targets were found. Figure 8 shows the potential target locations marked, as determined from the SOCS GPR SAR image. CNR analysis was used to eliminate clutter and estimate the lengths of the targets. The true locations of the buried ordnance were not available to Battelle.

AIRBORNE GROUND PENETRATING RADAR

Airborne System Description

Battelle and The Ohio State University ElectroScience Laboratory also built the airborne ground penetrating radar system to address the problem of locating and identifying buried unexploded ordnance at military sites. The goal of this effort was to demonstrate an airborne test-bed ordnance characterization system. Battelle coordinated the construction of the airborne system. ESL provided the GPR, the GPR antenna, and the complex natural resonance-based discrimination processing. Battelle is providing the synthetic SAR processing of the data as a post-processing step. The Ohio State University Center for Mapping (CFM) provided navigation and positional information to the system.

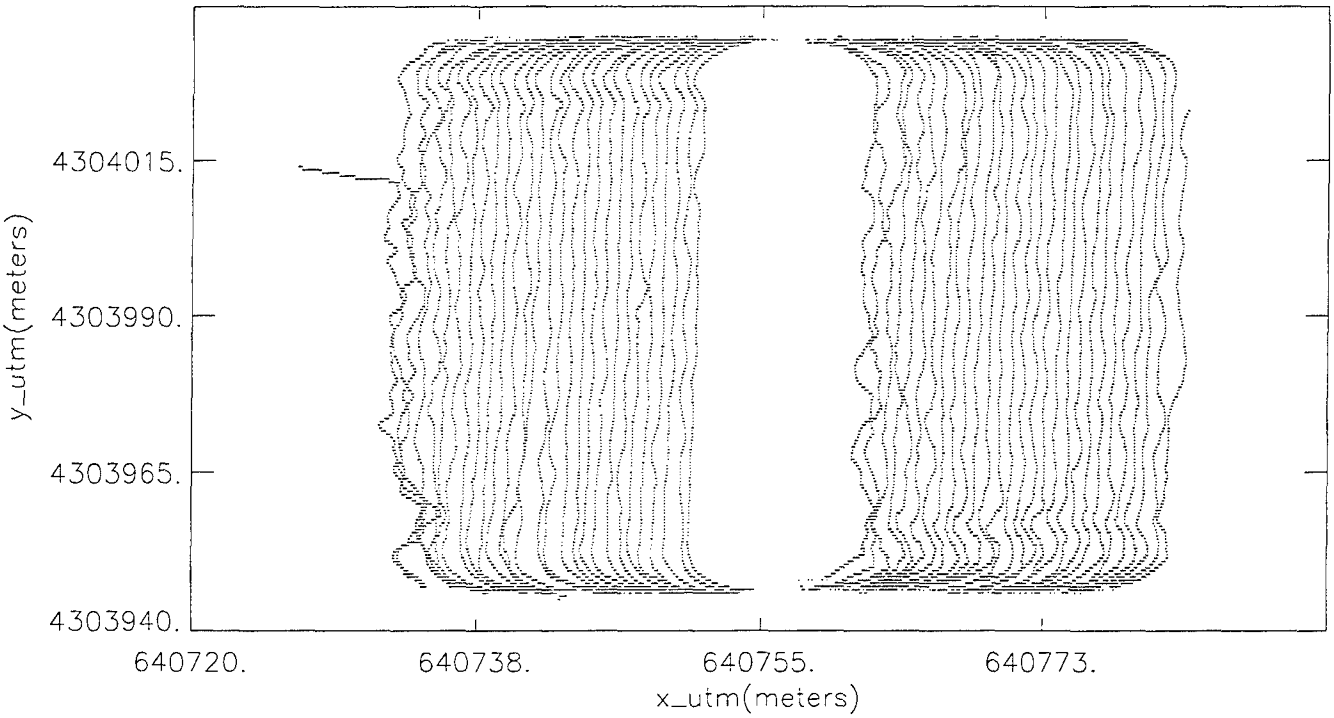

Figure 6 SOCS GPR Path At JPG Area C22.

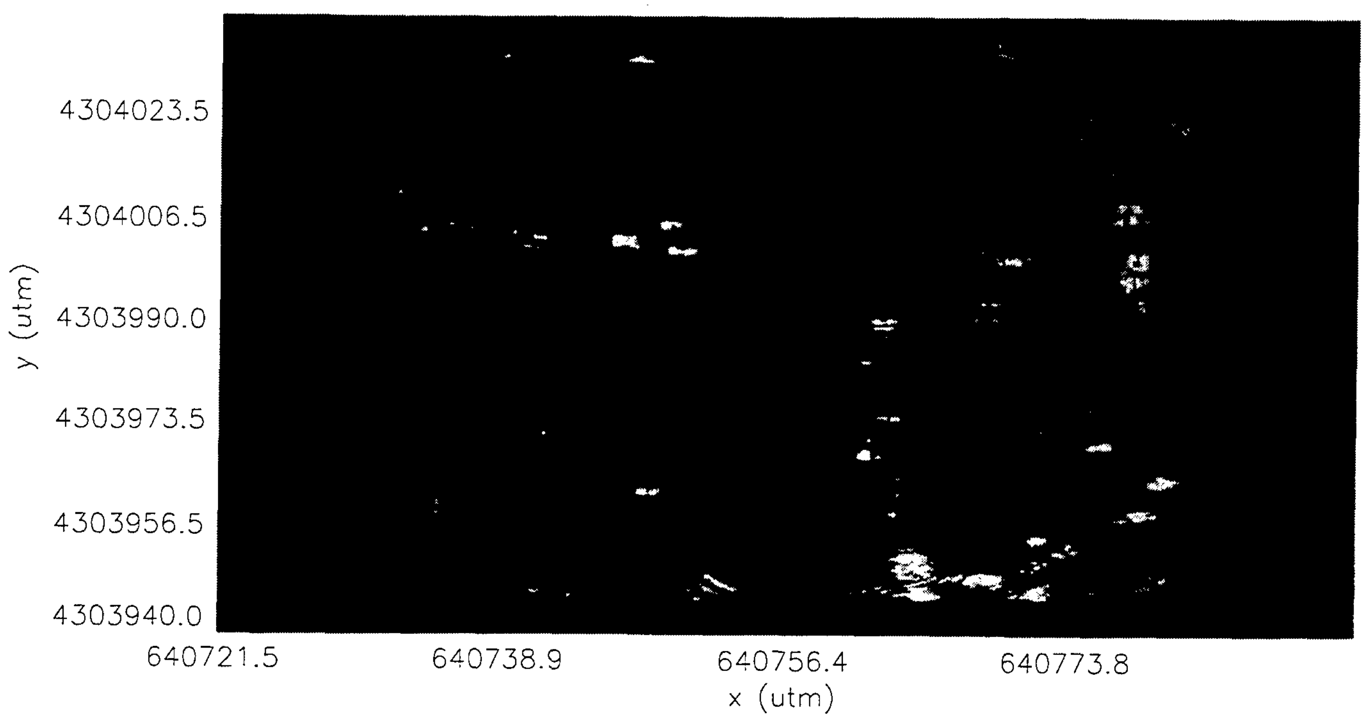

Figure 7 SOCS GPR Collapsed Image At JPG Area C22.

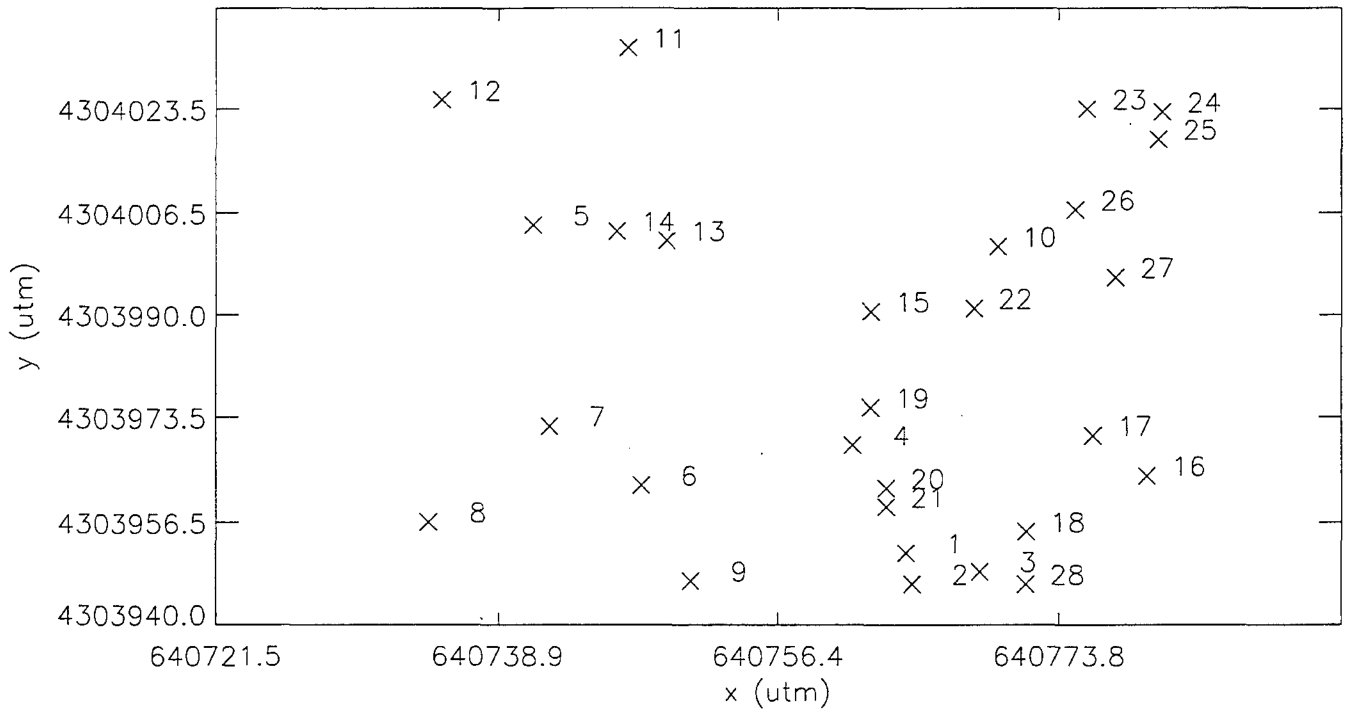

Figure 8 SOCS GPR JPG Potential Target Locations.

The airborne GPR is a stepped-frequency system. The GPR antennas are located below and on the sides of a UH-60 (Blackhawk) helicopter. SAR processing is performed in the frequency domain because of the slow stepping speed of the radar and the constant motion of the helicopter. The airborne radar sweeps from 50 to 700 MHZ in four seconds while the helicopter flies over the test area approximately 25 meters above the surface at the rate of a few feet per second. Multiple passes are made over the test pad to collect the GPR data. The transmit antenna is a vertical cone lowered beneath the aircraft. Two antennas on either side of the helicopter receive the scattered signal. The raw data is in the form of an amplitude and phase at each of the discrete frequencies and the position at which the data point was acquired. Position information is obtained from a GPS antenna on the tail of the helicopter and an internal inertial navigation system. This configuration allows positional accuracies on the order of 10 cm with approximately 25 updates per second.

Airborne Data Analysis

Synthetic aperture radar processing of the frequency domain airborne GPR data consists of defining the volume to be imaged, collecting frequency domain GPR data, and constructing the image. The image is constructed by summing each phase adjusted complex frequency domain data point for each voxel in the image.

In order to process the GPR data, the dielectric constant of the soil and the position of the GPR antenna at the point in time at which each frequency in each scan is transmitted and received are required. The position of the GPR antenna on the helicopter is measured using a combined global positioning system and inertial navigation system (GPS/INS). The UTM coordinates of the GPR antenna were recorded as a function of time along with the pitch, roll and yaw of the helicopter. The UTM coordinates of three positions on the surface are also measured. Each frequency scan from the GPR and the time are recorded separately. Interpolation is used to determine the location of the GPR antenna at each frequency within each frequency scan.

Airborne GPR Image Construction

In the airborne GPR, only one of the N frequencies from 50 MHZ to 700 MHZ is transmitted at each position of the radar. The frequencies are scanned as the radar moves along the flight path. The sequence of frequencies is repeated M times for a given image. The received signal $s(m,n)$ is an M by N array of complex values equal to the sum of the responses from each voxel of the imaged volume. m is the radar position index and n is the frequency index. The image value for the voxel at coordinates (x, y, z) is:

$$I(x,y,z) = \frac{1}{M} \sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} s(m,n)\ e^{jk_{1n}R(x,y,z,m,n)}$$

where

$$R(x,y,z,m,n) = r_1 + \frac{k_{2n}}{k_{1n}} r_2 + \frac{k_{2n}}{k_{1n}} r_3 + r_4 \qquad \textbf{(9)}$$

k_{1n} is the propagation constant in air, and k_{2n} is the complex propagation constant in the soil. r_1 is the distance from the transmitter to the surface, r_2 is the distance from the surface to the voxel at coordinates *(x,y,z)*, r_3 is the distance from the voxel at *(x,y,z)* to the surface, and r_4 is the distance from the surface to the receiver. The ranges, r_1, r_2, r_3, and r_4 shown in Figure 9, must be calculated from the transmitter to each voxel and back to the receiver for each radar position. The angles and ranges can be calculated from the soil characteristics and the coordinates of the transmitter/receiver and each voxel in the image. Let (x_1, y_1, z_1) be the coordinates of the transmission point and let *(x, y, z)* be the coordinates of the image point. θ_1 is the plane wave angle of incidence in air and θ_2 is the angle of incidence in the soil. The following method (Roy, et al.,1990) is used to calculate the ranges in each medium from the transmitting antenna to the image point and back to the receiving antenna. From Snell's Law,

$$\sin\theta_2 = \frac{\sin\theta_1}{\eta(\theta_1)} \qquad \textbf{(10)}$$

where

$$\eta(\theta_1) = \frac{1}{\sqrt{2}} \sqrt{\epsilon_r + \sin^2\theta_1 + \sqrt{(\epsilon_r - \sin^2\theta_1)^2 + (\frac{18\,\sigma}{f})^2}}$$

and *f* is the frequency in gigahertz. From the geometry,

$$x - x_1 = y_1 \tan\theta_1 - y\tan\theta_2 \qquad \textbf{(12)}$$

We use an iterative procedure on this equation and Snell's Law to solve for θ_1, then we find the angle θ_2 and ranges r_1 and r_2:

$$r_1 = \frac{y_1}{\cos\theta_1}\ ,\ r_2 = \frac{y}{\cos\theta_2}\ . \qquad \textbf{(13)}$$

A similar calculation is performed to find r_3, r_4, θ_3, and θ_4. If the transmit and receive antennas are at approximately the same position, $r_1 = r_4$, *and* $r_2 = r_3$.

Airborne GPR Results

The Airborne GPR helicopter was flown over the Tyndall AFB UXO test pad. The paths that were flown are shown in Figure 10. The altitude of the helicopter ranged from 24 to 27 meters above the surface of the ground. The velocity of the helicopter was 0.2 to 0.5 m/s. Segments of the path that are not over the Tyndall test pad are not shown. Some segments of the paths over the test pad are missing due to gaps in the GPS/INS position data.

In order to characterize the transmitting and receiving antennas, a large corner reflector was placed in the center of the test pad. We are still working on a method to characterize the Airborne GPR antenna from the limited data we have.

CONCLUSIONS

The SOCS GPR results are promising. Most of the buried ordnance was located and we understand why the remaining pieces were not found. Fewer targets were located at JPG with the SOCS GPR, but the soil conditions were much worse there. Operational and optimization issues remain to be resolved for both the SOCS GPR and the Airborne GPR. Data processing is continuing on the Airborne GPR data.

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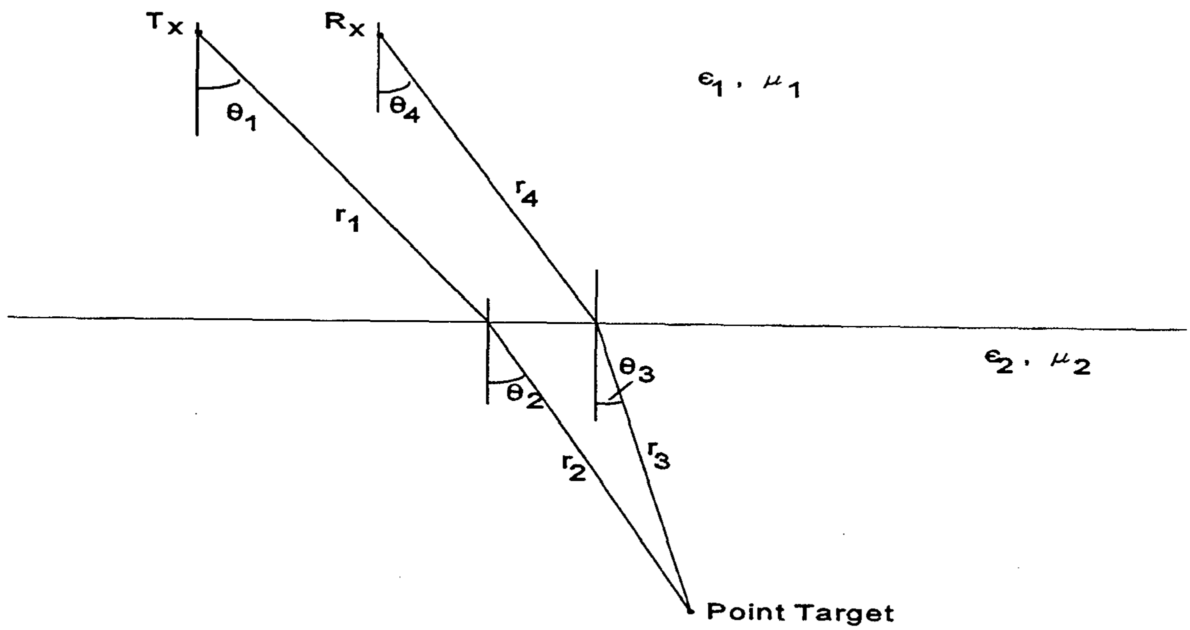

Figure 9 Airborne GPR Range and Incident Angle Definitions.

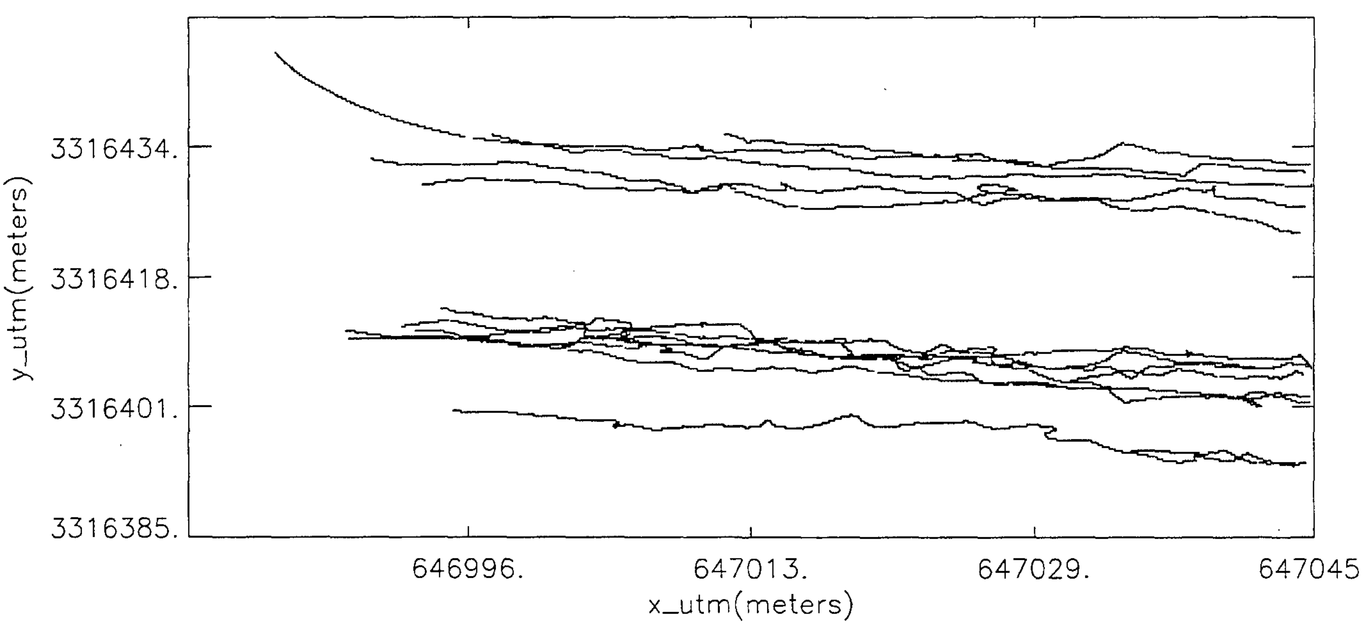

Figure 10 Airborne GPR Flight Path over the Tyndall Test Pad.

Ground Penetration Radar Target Classification via Complex Natural Resonances

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ABSTRACT

This paper describes an UXO classification technique using the complex natural resonance (CNR) signature extracted from the radar data. The first resonant mode is then used to estimate the UXO length. TLS-Prony method is used here for CNR extraction. A theoretical application example is demonstrated by processing the calculated field for an UXO model via the moment method for body of revolution. The predicted lengths for measured data with real UXOs buried in beach sand agree closely with their true lengths.

INTRODUCTION

Although the CNR classification technique has been applied to targets in free space, it still difficult to apply this technique to ground penetration radar (GPR) data for conducting targets. Unknown medium property, inhomogeneity and ground loss are the major limitations. It is also difficult to obtain an accurate damping factor in the presence of clutter signal and noise. For many practical cases, the extracted damping factors are usually not sufficiently reliable for classification purpose.

A Prony-based method will be used to extract the CNR and is discussed in next section. Since the CNR signature is independent of radar aspect angle, further processing gain can be obtained by using multiple looking data. Some auxiliary processing techniques such as time-frequency processing, position-frequency processing and late-time spectrum are also incorporated to enhance the performance.

Most UXOs have simple elongated bodies and tend to resonate like conducting rods when illuminated by a radar pulse. Practically, only a few (less than three) dominant CNRs can be found from GPR data due to the medium loss, radar sensitivity and antenna bandwidth. In this paper, we will use the equivalent free space resonant length (half wavelength) obtained from the lowest resonant frequency to estimate the length of each UXO. This is verified by analyzing a numerical UXO model in the second section.

Finally, an practical UXO classification example is given. The data was collected using the autonomous Subsurface Ordnance Clearance System (SOCS) at Wright Labs, Tyndall AFB test site where known UXOs were buried in beach sand at various depths and orientations.

PRONY METHODS

Consider a time domain waveform, $f(t)$, which can be expressed as

$$f(t) = \sum_{m=1}^{N} c_m e^{s_m t} u(t) \tag{1}$$

where $s_m = \alpha_m + j2\pi f_m$ are poles in the complex frequency plane, α_m and f_m are damping factors and resonant frequencies associated with the mth CNR mode. Complex amplitudes, c_m, are the residues associated with poles. $u(t)$ is a unit step function. Note that s_m should appear in complex conjugate pairs if $f(t)$ is real. It has been shown that late time portion of an impulse response from a radar target has the same form as $f(t)$ [1] [2] [3] [4].

The discrete version of Equation (1) is expressed as

$$f((n-1)\Delta t) = \sum_{m=1}^{N} c_m e^{s_m (n-1)\Delta t}, \qquad n = 1, \ldots, L, \tag{2}$$

where Δt is the sampling period which should satisfy Nyquist sampling criteria to avoid aliasing of higher modes. N is the total number of CNRs and $L = 2N$ is the number of data points. The above equation will be rewritten in the following simpler form for convenience.

$$f_n \equiv f((n-1)\Delta t) = \sum_{m=1}^{N} c_m z_m^{n-1}, \qquad n = 1, \ldots, L, \tag{3}$$

where $z_m = e^{s_m \Delta t}$. The above equation was solved by Prony in 1795 [5] by realizing that f_n also satisfies

$$f_n = -\sum_{m=1}^{N} a_m f_{n-m} \qquad \text{for} \qquad N+1 \leq n \leq 2N. \tag{4}$$

where the coefficients a_m can be solved using the $2N$ data points, $f_1, f_2, \ldots, f_{2N}$, and the following matrix equation $\mathbf{Fa} = \mathbf{f}$, ie. ,

$$\begin{bmatrix} f_N & f_{N-1} & \cdots & f_1 \\ f_{N+1} & f_N & \cdots & f_2 \\ \vdots & \vdots & \ddots & \vdots \\ f_{2N-1} & f_{2N-2} & \cdots & f_N \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix} = - \begin{bmatrix} f_{N+1} \\ f_{N+2} \\ \vdots \\ f_{2N} \end{bmatrix}. \tag{5}$$

Applying complex Z-transform to the above difference equation, one can easily show that the coefficients a_m are also the coefficients of the following Nth order characteristic polynomial

$$1 + a_1 z^{-1} + a_2 z^{-2} + \ldots + a_N z^{-N} = 0. \tag{6}$$

The roots for the above equation then give the poles $z_m = e^{s_m \Delta t}, m = 1, 2, \ldots, N$. Using Equation (3), the residues, c_m can then be found by solving the matrix equation $\mathbf{Zc} = \mathbf{f}$, ie. ,

$$\begin{bmatrix} 1 & 1 & \cdots & 1 \\ z_1 & z_2 & \cdots & z_N \\ \vdots & \vdots & \ddots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \cdots & z_N^{N-1} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_N \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_N \end{bmatrix}. \tag{7}$$

The above three-step procedure for extracting poles, z_m, and the residues, c_m is called the *Prony method.* If $L > 2N$, Equation (4) is simply a forward linear prediction for $N+1 \leq n \leq L$. In this case, coefficients a_m can be solved in a least square error sense. This modified Prony method is known as *extended Prony method* or *LS-Prony method* [6] [7]. The least square error solution can be achieved by replacing Equation (5) by $(\mathbf{F}^{\mathbf{H}}\mathbf{F})\mathbf{a} = \mathbf{F}^{\mathbf{H}}\mathbf{f}$. Note that LS-Prony method is equivalent to the covariance method of linear prediction [8][9]. It has been found that for high SNR data, LS-Prony gives better results than a traditional Prony method. When the data contains noise, both left hand side data matrix $\mathbf{F}$ and right hand side vector $\mathbf{f}$ in Equation (5) are contaminated. Kumaresan-Prony method [10] considers the contaminated matrix only and applies singular value decomposition (SVD) to reduce the noise effect by matrix and vector truncation such that the contributions from insignificant singular values are removed. Kumaresan-Prony method shows a great improvement over the traditional Prony Method for noisy data. TLS-Prony method takes one step further by including the contaminated vector $\mathbf{f}$ in the square error minimization process. A similar truncation process and SVD are also used to obtain LSE curve fitting. More details about this algorithm can be found in [11].

NUMERICAL UXO MODEL

Most of UXOs are rotationally symmetric and can be numerically modeled using the body of revolution moment method code. The scattered field for a UXO in free space can then be easily calculated. Fig. 1 shows the geometry of a model to be analyzed. The calculated normal incidence backscattered field as a function of frequency is plotted in Fig. 2. The time domain impulse response is then obtained using inverse Fourier transformation. Fig. 3 shows the time-frequency distribution obtained by applying the TLS-based Prony algorithm [11] to find the CNR's within a running window which contains a subset of the whole waveform. The magnitude of CNRs is shown in gray scale. One can see that the dominant resonance frequency of about 200 MHz is less damped compared to the third harmonic CNR (at 600MHz). 200 MHz in air corresponds to an estimated length of 30 inches, which is about 20% longer than the true physical length (25.5 inches). This is a well known phenomenon, similar to the resonant length of an electrical dipole. The amount of overestimation depends on the shape of the UXO. The time-frequency representation shown here can help separate the early time and late time signals as well as different resonant groups for complex shape targets. Body of revolution moment method can also be used to calculated the scattered field for UXO immersed in a homogeneous medium [12].

CNR FROM MEASURED DATA FOR BURIED UXO

The CNR's of conducting scatters buried in a homogeneous medium with known electromagnetic property have been predicted by Baum [1]. That is,

$$S = -\frac{\sigma}{2\epsilon_0\epsilon_r} + [(\frac{\sigma}{2\epsilon_0\epsilon_r})^2 + \frac{(S^{(0)})^2}{\epsilon_r}]^{1/2}, \tag{8}$$

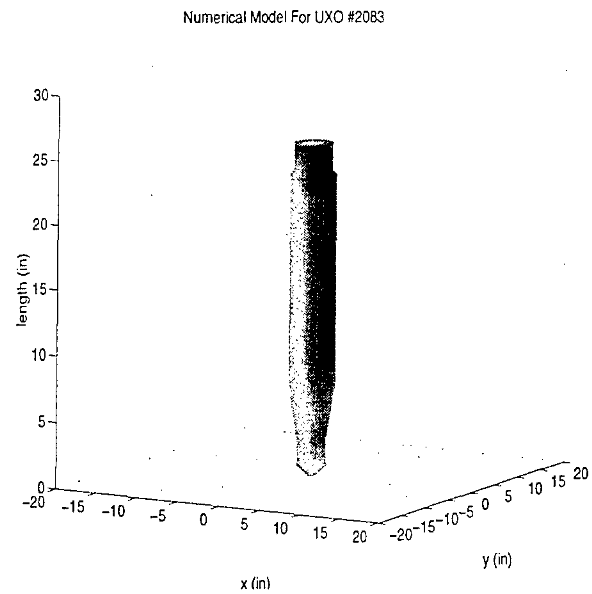

Figure 1: Example of numerical UXO model.

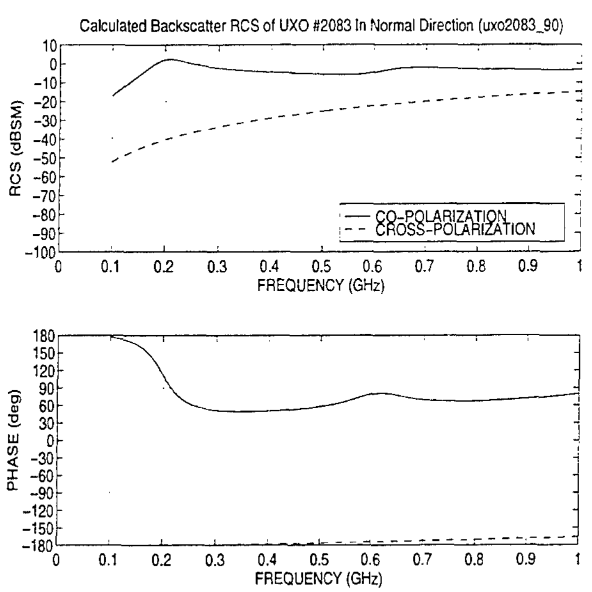

Figure 2: Normal incidence RCS of the previous UXO model.

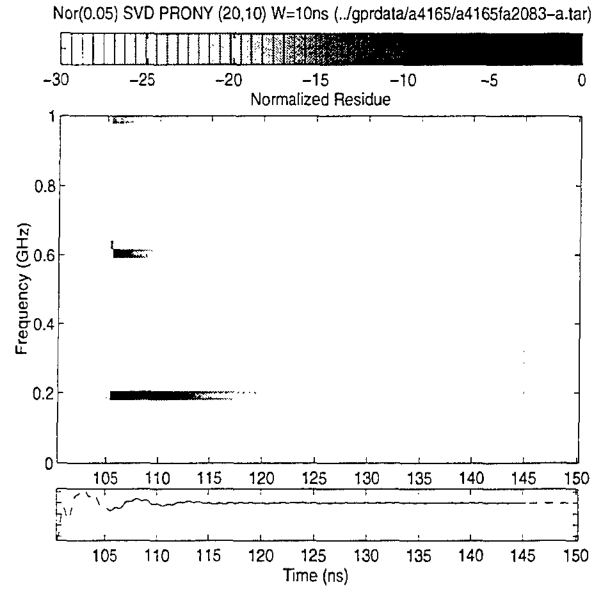

Figure 3: Time-frequency plot of the extracted CNRs.

where $S = \alpha + j\omega$ and $S^0 = \alpha_0 + j\omega_0$ are the poles associated with the CNR's in the medium and free space, respectively; σ and ϵ_r are the conductivity and permittivity of the medium. From this relationship, only one data base containing the free space CNR's for targets of interest is required for target identification. Theoretically, more precise identification requires both the resonance frequencies and the damping factors; however, the damping factor is usually quite unstable, especially when there is clutter or noise. First order target classification can also be achieved by estimating the resonant length of the target from the dominant resonance frequency and the soil parameters.

In a recent test at Wright Labs, Tyndall AFB, an OSU/ESL designed cross-polarization antenna was used to measure three known reference conducting rods as shown in Fig. 4. The results are shown in the gray scale map of Fig. 5. The permittivity and conductivity of the medium is 5 and 4 mmho,respectively. One can clearly see the typical arcs due to varying signal delays from the targets. The data was un-calibrated but preprocessed and gated to select each candidate target. CNR is then extracted using TLS Prony method. The right most target is arbitrarily picked as an example. The results are plotted in Fig. 6. Two CNR's were found in the windowed region. The resonance frequencies of the dominant CNR and its second harmonic are 72 MHz and 145 MHz, respectively. This corresponds to a 3.1 foot resonant length in free space, which is very close to the true target length – 3 feet ! The same technique has been used to identified a group of UXO's buried under sand with different depths, orientations

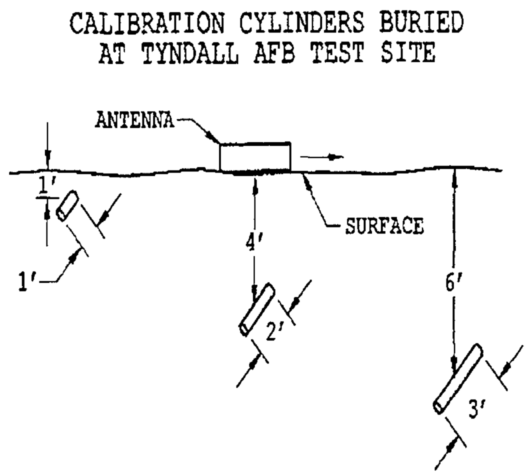

Figure 4: Layout of conducting rods buried in ground.

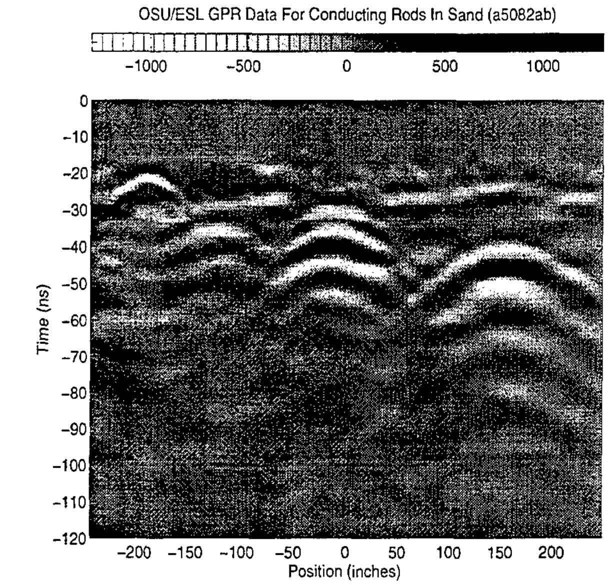

Figure 5: Waterfall plot with its ensemble average removed.

and inclinations. The results are summarized in Table 1. It is noticed that difference between the true length and the estimated length exists. This is related to the induced electrical current flowing on the body of a UXO. This difference is a function of the UXO's shape and the property of surrounding medium. For short UXO (8 inch shell), the resonant frequency falls outside the antenna's optimum band. The response is too weak to extract reliable CNR.

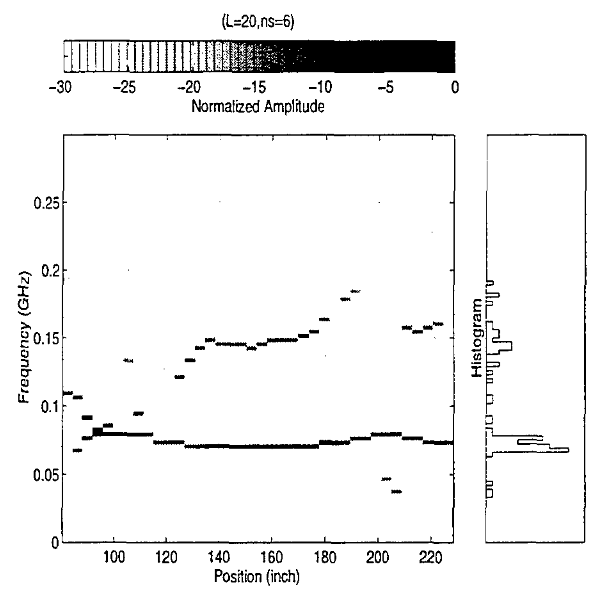

Figure 6: Position-frequency plot of CNR extracted from gated data.

CONCLUSION

This paper discussed the difficulties and feasibility of using CNR technique to perform UXO classification. Both analytical and measurement examples were given. The processed result for a real test site surveyed data has shown that CNR technique could provide an estimation of anomalies' lengths which are then used as an indicator of UXO's presence. During the course of this study, it was also found that the loss and inhomogeneity in medium post two major difficulties. More site measurements with known buried targets in varieties of soil conditions would benefit the study substantially. In order to perform CNR classification technique successfully and efficiently, a wide frequency band antenna and a high sensitivity radar are two key components.

ACKNOWLEGEMENT

This research was carried out in cooperation with Battelle and was funded by NAVEODTECHDIV.

Table. 1 The depths and dominant CNR's obtained from the GPR measured data of known targets buried in sand ($\epsilon_r \approx 5, \sigma \approx 3$mmho).

Target Type	Apparent Depth (ft)	Predicted Length (in)	Actual Length (in)
1' cylinder	1.0380	12.5276	12
2' cylinder	3.6636	23.6589	24
3' cylinder	5.8958	36.7477	36
UXO 2000lb	5.1290	91.3949	90
UXO 8" shell	2.0681	33.2713	30
UXO 81mm	2.4577	20.4558	18
UXO 60mm	1.3089	17.8330 *	8
UXO BDU33	4.7387	34.5935 **	25
UXO BDU33	4.3606	34.6632 **	25
Russian mortar	2.8944	25.7129	22.5

"*" the resonant frequency of this target falls beyond the available system bandwidth
"**" the discrepancy is assumed to be due to some unknown physics associated with this type of target

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HIGH ACCURACY CM-LEVEL GPS/INS POSITIONING FOR AIRBORNE GROUND PENETRATING RADAR (GPR) SAR PROCESSING

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ABSTRACT

Proper focusing of the Airborne Ground Penetrating Radar measurements for Synthetic Aperture Radar processing requires high accuracy (0.07 m) and high rate (25 Hz) positioning. For this purpose the Center for Mapping has developed a high accuracy, high rate GPS/INS positioning system for airborne applications. This system employs On-The-Fly ambiguity resolution techniques capable of providing high accuracy cm-level positioning with initialization times of 5 sec-10 sec with as few as five satellites in view. Integration of high accuracy (cm-level) GPS positions with inertial navigation measurements, provides high rate positioning between the 1 sec (1 Hz) GPS position updates, and during periods when GPS positions are not available due to aircraft banking, or due to interference with the rotating blades. This paper describes the integrated GPS/INS system and the positioning accuracy obtained during the airborne GPR demonstration, for unexploded ordnance detection, identification, and remediation. This demonstration was conducted in November of 1995, at Tyndall Air Force Base, Panama city, Florida.

INTRODUCTION

Funded by the U.S. Army Environmental Center, the main purpose of the contract N00174-94-C-0066 is to demonstrate an airborne ground penetrating radar (GPR) system and apply it to the problem of locating and identifying buried unexploded ordnance (UXO) at military sites [Battelle, 1995]. The effort is being monitored by the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV). The emphasis of the research is to apply and demonstrate airborne GPR that will allow large parcels of land to be processed.

This contract presents one portion of the UXO Clearance Technology Program, an overall U.S. Government program to clear former and present military ordnance range of all unexploded ordnance and other buried devices that pose a threat to the public. As part of this Government effort, Battle, The Ohio State University, and other contractors and Government agencies are demonstrating techniques that can rapidly and reliably determine the boundaries of contaminated sites and the concentration of buried unexploded ordnance at those sites.

The goal of second phase of this program is to demonstrate a test-bed ordnance characterization system. Battelle is providing a focal point for the airborne system, synthetic aperture radar processing to the data in a post-processing step. As a subcontractor, The Ohio State University Center for Mapping (CFM) is providing navigation and positional information to the system. The Ohio State University ElectroScience Laboratory (ESL) is providing the GPR, the GPR antenna, and the complex natural resonance-based discrimination processing.

The system was demonstrated to the Government during November 1995. The assets of the U.S. Army Aviation Technical Test Center (ATTC) at Fort Rucker, near Dothan, Alabama, was used in the demonstration. The Airborne GPR was tested at Fort Rucker and demonstrated at Tyndall AFB.

Proper focusing of the Airborne Ground Penetrating Radar measurements for Synthetic Aperture Radar (SAR) processing require high accuracy and high rate positioning. For this purpose the Center for Mapping has developed a high accuracy, high rate GPS/INS positioning system for airborne applications. This system employs On-The-Fly ambiguity resolution techniques capable of providing high accuracy cm-level positioning with initialization times of 5 sec-10 sec with as few as five satellites in view [Dedes, 1995]. This is very important for airborne applications in a helicopter environment, since tracking of all the satellites may not be possible due to the interference of the satellite signals with the rotating blades.

Integration of high accuracy (cm-level) GPS positions with inertial navigation measurements, provides high rate positioning between the 1 sec (1 Hz) GPS position update, and during periods when GPS positions are not available due to aircraft banking, or due to interference with the rotating blades. In the following sections, we present a brief overview of the INS used in the flight tests, a description of the quality of the test data, and the accuracy of GPS/INS positioning during the airborne GPR

demonstration. Recommendations for further system development are also included.

INS SYSTEM OVERVIEW

The INS employed in these experiments was the K600A297-01 navigator [Kearfott, 1994], produced by Kearfott Guidance & Navigation Corporation for the ATTC. The K600A297-01 is an integrated GPS/INS system with a positioning accuracy of 16 m (SEP) when the GPS P(Y) code is available. During the flight tests, the GPS antenna of the K600A297-01 was disconnected to force the system to work in pure inertial mode without any GPS updates. Pure inertial measurements are required for optimal integration with high accuracy (cm-level) differential GPS positioning.

The K600A297-01 navigator uses the T-24 Ring Laser Gyro (RLG), and the MOD VII Accelerometer in its Inertial Sensor Assembly (ISA). T-24 RLG is a monolithic 3-axis angular displacement sensor providing excellent drift and random walk characteristics due to the 24 cm path length and the inherently stable thermal characteristics. MOD VII is a three single-axis linear acceleration sensor providing excellent bias and scale factor stability due to the rugged gas-damped inertial mass and rare-earth magnet construction. The accuracy of the resulting INS system without any GPS updates is as follows:

Velocity (1 m/s axis rms)
Position (< 1 nm/hr CEP)
Attitude (Roll, Pitch, 0.05 deg rms)
Heading (0.1 deg rms)
Linear Acceleration (2 ft/s/s rms)
Angular Acceleration (10 deg/s/s rms)

When cm-level GPS positions are available, the errors affecting the Inertial Measurements can be estimated to a high degree of accuracy, increasing the accuracy of the GPS/INS positioning significantly.

INS DATA STRUCTURE

The INS I01 Message from the K600A297-01 was recorded during flight tests for post processing. The I01 Message includes the INS navigation mode, position, velocity, attitude, heading, linear acceleration, angular rate, and the INS error status. This Message is available for every 20 msec (50 Hz). The resolution of the INS output data is as follows:

velocity (3.8147e-6 ft/s)
attitude and heading (3.05176e-5 pi rad)
linear acceleration (0.03125 ft/s/s)
angular rate (1.22070e-4 pi rad/sec)

The positioning information from K600A297-01 is not used in post processing, because the resolution accuracy of the INS positions is too low (4 ft), and the INS positioning errors without any GPS updates are very large (approximately 1 nm/h). For this reason an independent INS position integration algorithm was implemented in the CFM GPS/INS software.

INS DATA COLLECTION AND QUALITY

Six GPS and INS data sets were collected in the flight tests. Two data sets were collected on November 1 and 2, 1995 at Ft. Rucker. The other data sets were collected on November 7, 8 and 9, 1995 at Tyndall AFB. The data collection was successful, although there were the following unexpected problems:

1. Some of the INS data collected on November 1 was lost due to bad sectors on the hard drive of the on-board computer;
2. The INS data set collected on November 8 had several gaps, ranging from 100 to 1500 seconds in length;
3. The INS was working in degraded NAV mode on November 7 and 9 because of degraded initial alignment performance. (On November 9, the pilot did try to use normal alignment instead but he was not successful).

GPS DATA COLLECTION AND QUALITY

On-The-Fly ambiguity resolution was used for high accuracy (cm-level) differential GPS positioning, between a fixed reference position (base station), and the helicopter (rover station).

In order to determine the accuracy of the GPS positioning, two base stations were used and the resulting helicopter positions at each epoch were compared. The On-The-Fly ambiguity resolution, performed independently from the data of the two base stations, will yield positions differing at the decimeter-level if the incorrect ambiguities have been identified.

Figures 1, 2, and 3 show the comparison of the helicopter (rover) positions as computed from the two base stations using GPS data collected on November 8, 1995. This comparison shows an accuracy of approx. 0.005-0.015 m in the horizontal (north, east) directions and approximately 0.005 to 0.03 m in the vertical (up) direction.

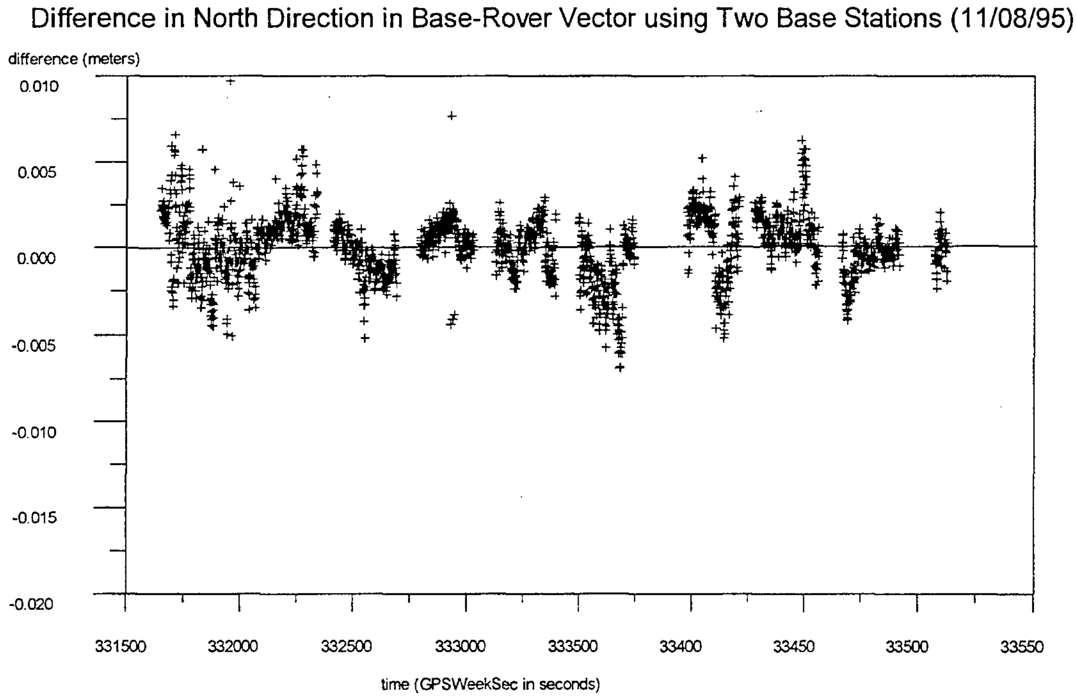

Figure 1. Difference in North in Base-Rover Vector calculated from Two Base Stations

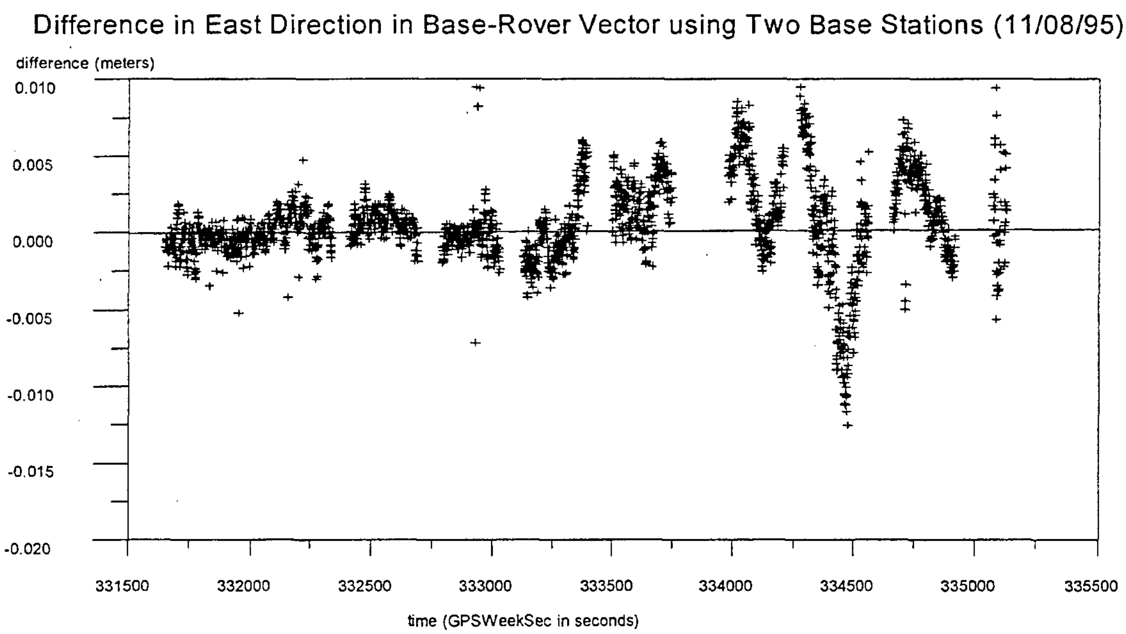

Figure 2. Difference in East in Base-Rover Vector calculated from Two Base Stations

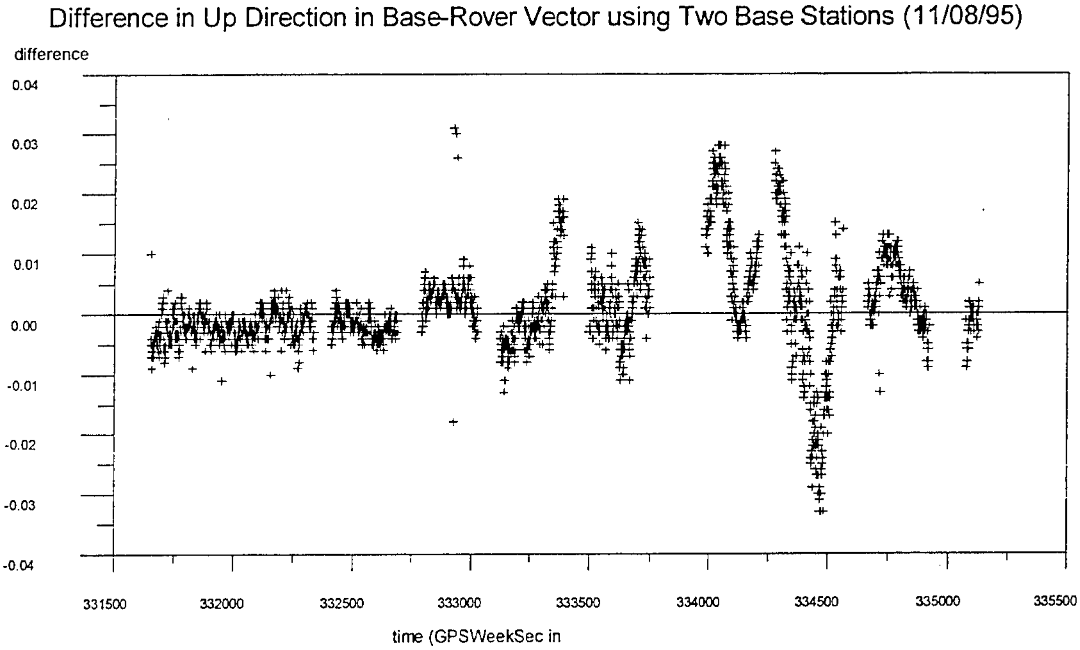

Figure 3. Difference in Up in Base-Rover Vector calculated from Two Base Stations

ESTIMATION ALGORITHM

In the GPS/INS system, the extended Kalman filtering algorithm was applied to calculate the estimate as a function of time and the measurement data. The algorithm includes the time-update and measurement-update steps. A filtering algorithm utilizes all of the past data to estimate the system state vector. For a post data processing case, it is desirable to use not only the past measurements but also the future measurement data to estimate the system state vector in order to achieve better estimation accuracy. In this case, a smoothing technique, which uses all measurements, say between time $t=0$ to $t=T$ to estimate the states of a system at a certain time t $(0 \le k \le T)$, may be applied.

The smoothing algorithm applied here is a combination of two extended Kalman filters. One of the filters, called a "*forward filter,*" operates on all the measurements up to and including time t and produces the estimate $x_F(t)$; the other filter, called a "*backward filter,*" operates on all the data after time t and produces the estimates $x_B(t)$. Then a smoothing algorithm may be used to combine these two estimates to get optimal smoothing estimates [Gelb, 1979].

The standard Kalman filter algorithm is sensitive to computer roundoff and the numerical accuracy might degrade to the point where the results cease to be meaningful. The effects of numerical errors are generally manifested in the appearance of computed covariance matrices that fail to retain non-negative values (i.e., with non-negative eigenvalues). Several methods have been applied to improve accuracy and to maintain non-negativity and symmetry of the computed covariance. One common practice is to replace the Kalman measurement update equation with the so called stabilized Kalman filtering algorithm. However, the stabilized Kalman filtering algorithm needs much more arithmetic operation than the standard Kalman filtering algorithm. Even so, the stabilized Kalman mechanization may still lose numerical stability and give negative diagonal computed results.

Another way is to adopt square root filtering algorithms that have coherently better stability and numerical accuracy than does the standard Kalman filter. The improved numerical behavior of square root algorithms is due in large part to a reduction of the numerical ranges of the variables. Loosely speaking, one can say that computations which involve numbers ranging between 10^{-2N} and 10^{2N} are reduced to ranges between 10^{-N} and 10^{N}. Thus the square root algorithms achieve accuracy that is comparable with a Kalman filter that uses twice their numerical precision.

In our system, the Bierman's U-D factorization algorithm was implemented ($P=UDU^T$, with U being upper triangular and D diagonal matrices) [Bierman, 1977]. The algorithm is considered to be of the square root type since $UD^{1/2}$ is a covariance square root of P. The U-D factorization algorithm has the accuracy characteristic of square root algorithms and does not involve scalar square roots. Thus, it qualifies for use in real-time applications. The U-D algorithm is considerably more efficient than

most of the square root covariance algorithms and is in fact almost as efficient as the standard Kalman algorithm.

GPS/INS DATA PROCESSING STRUCTURE

There are several major design and implementation factors used to achieve high accuracy in the GPS/INS system, including the GPS On-The-Fly ambiguity resolution technique mentioned above, and the feedback error calibration technique implemented in the INS position computation loop (closed-loop). In an open-loop configuration, the internal INS position errors are not corrected and as a result these errors increase with flight time. In the closed-loop configuration, as implemented in CFM's GPS/INS system, the INS position errors are limited to cm-level when the GPS is available at a 1 second rate. This greatly reduces the errors in the system model (a linearized form of the nonlinear navigation equation), and thus increases the estimation accuracy of the optimal estimator implemented in the GPS/INS system. The data processing structure for the GPS/INS system is shown in Figure 4.

SYSTEM PERFORMANCE

The performance of the integrated GPS/INS system using actual flight data, was determined from the analysis of the difference between the predicted INS positions and the estimated GPS positions. The results show that difference between these positions is at 0.01 m (1 σ) level for all data sets, even when the INS was operating in degraded NAV mode (data sets collected on November 7 and 9, 1995). Since the GPS positioning accuracy is at the 0.01-0.03 m (1 σ) level, the GPS/INS positioning accuracy must be at the 0.01-0.04 m (1 σ) level for the times when cm-level GPS positions are available. In addition, the INS velocity error is less than 1 cm/s (1 σ).

CONCLUSIONS

In this paper a high accuracy integrated Global Positioning System/Inertial Navigation System was presented. This system is capable of providing highly accurate position data in real-time or in post processing. A number of issues involved in designing the integrated GPS/INS were discussed, including the application of optimal estimation algorithms, GPS On-The-Fly ambiguity resolution technique, and GPS/INS integration structure, etc. The data processing results showed that the loose GPS/INS integration worked well with actual flight test data. These results confirmed that the GPS/INS system is able to achieve positioning accuracy at the 0.04 m (1 σ) level when GPS positions are available at a 1 second rate with an accuracy of 0.01-0.03 m. The disadvantage of the loose GPS/INS integration is that the positioning is performed on the basis of INS measurements alone when the number of tracked GPS satellites drops below four. This occurs when the helicopter maneuvers. The only solution to this problem is to implement tight GPS/INS integration which allows use of GPS measurements from less than four satellites. Furthermore, tight GPS/INS integration provides faster and more reliable On-The-Fly ambiguity resolution after short periods of complete loss-of-lock to the GPS satellites.

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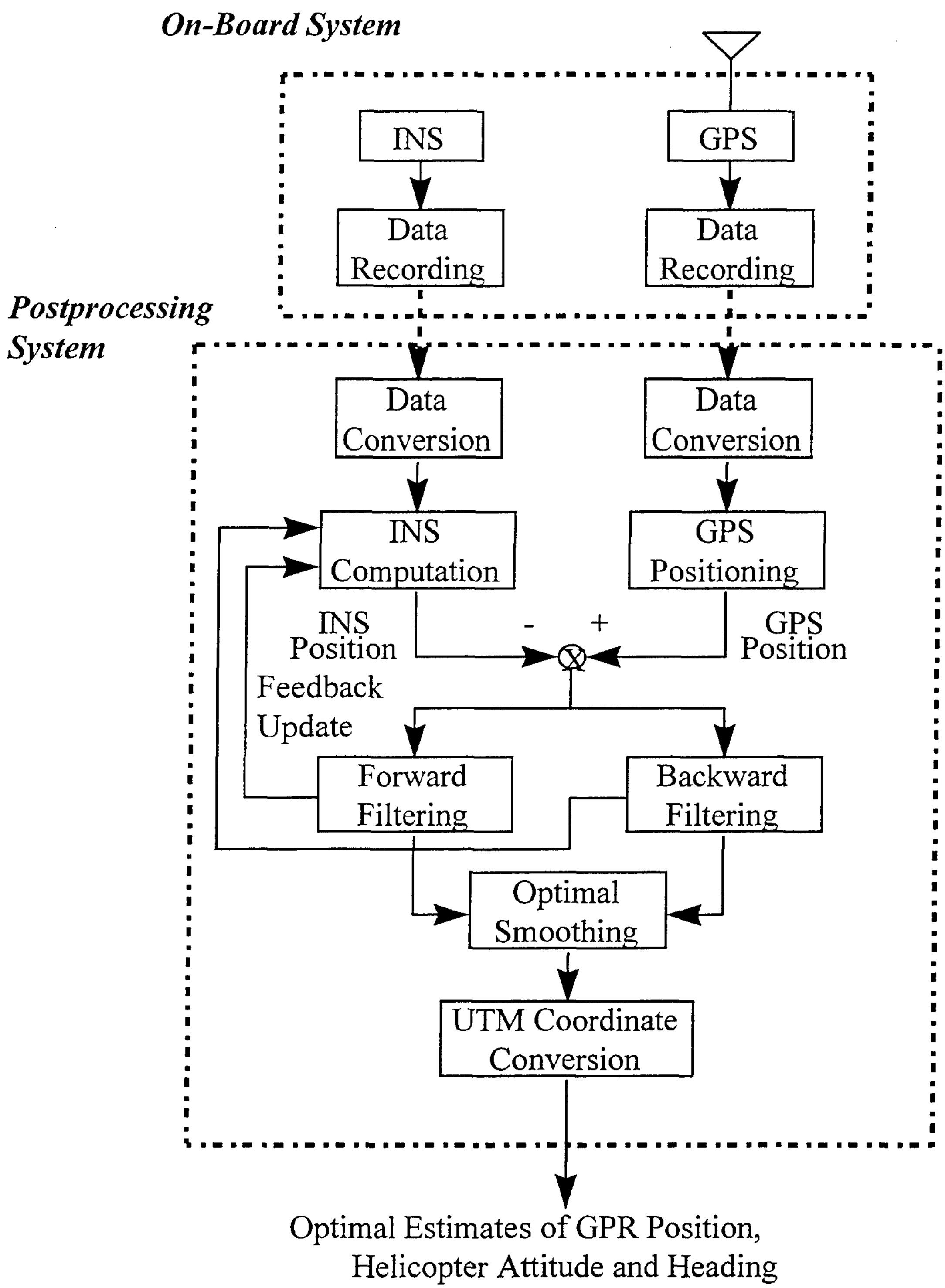

Figure 4. The Data Processing Structure for the GPS/INS Program

RESULTS AND ANALYSIS OF THE 1995 YUMA GROUND PENETRATING RADAR EXPERIMENT*

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Abstract

In July and October 1995, and again in January 1996, MIT Lincoln Laboratory and Army Research Laboratory conducted the data collection portion of a ground penetrating radar experiment at the U.S. Army Yuma Proving Ground in Arizona. Three radar systems (the SRI Folpen III, the ARL BoomSAR, and the Navy P-3) collected polarimetric radar data from both targets and clutter. Some of the various target deployments included a minefield, wires/pipes, and missile clones. Some radar data were processed into SAR imagery exhibiting better than 1 m x 1 m resolution. This paper describes the experiment and presents some preliminary results derived from data collected using the Folpen III and BoomSAR systems.

1. Introduction

Over the last few years, there has been a strong interest in applying airborne synthetic aperture radar (SAR) to the wide-area survey of underground targets, in both military and civilian situations. As part of an investigation to understand ground penetrating radar (GPEN) phenomenology, a large scale field experiment was conducted by MIT Lincoln Laboratory (MIT/LL) at the U.S. Army Yuma Proving Ground (YPG) in Arizona from June 4 to 15, 1993 [1,2]. This experiment produced a unique and rich source of information concerning GPEN radar phenomenology. Among the targets deployed for the 1993 experiment was a minefield. SAR data were collected using the SRI Folpen II ultra-wideband radar system, and processed into SAR imagery. The minefield was successfully detected by applying a group detection algorithm [3] to the SAR imagery; the imagery had a greater than 10 dB target-to-clutter ratio (T/C) for metallic anti-tank mines in the desert terrain.

To supplement the data gathered in the 1993 Yuma experiment, a second GPEN radar experiment was carried out by MIT/LL and Army Research Laboratory (ARL) at YPG. This experiment was referred to as the 1995 Yuma experiment. As in the 1993 Yuma experiment, a variety of targets, including mines, were deployed in 1995. The data collection portion of the experiment took place during three periods: July 1995, October 1995, January 1996.

The primary objectives of the 1995 Yuma GPEN experiment were: (1) to gather field data for investigating wide-area surveillance and detection of underground targets; (2) to gather field data for developing and validating models of relevant detection phenomenologies; and (3) to extend the range of measurement parameters such as polarization, depression angle, frequency band, and (4) to test new sensor technologies.

2. Description of the 1995 Experiment

2.1 Sensors

Three ultra-wideband radar systems (Figure 1) participated in the data collection: the SRI Folpen III airborne SAR (July and October 1995), the Navy P-3

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airborne SAR (July 1995), and the ARL ground-based SAR (BoomSAR) (January 1996).

The Folpen III system has dual co-polarizations; it is an impulse radar which transmits a pulse with a spectrum covering the 100-500 MHz band and receives in one of the 100-300 MHz, 200-400 MHz or 300-500 MHz band [4]. In the 1995 Yuma experiment, only the 200-400 MHz band with a norminal resolution of 1 m x 1 m was utilized.

The P-3 radar is fully polarimetric; it is an FM chirp radar which operates in the 200-700 MHz band with a norminal resolution of 0.3 m x 0.6 m [5].

The BoomSAR [6] was jointly developed by ARL and MIT/LL. ARL developed the radar hardware, and MIT/LL participated in platform design, and motion compensation system. The BoomSAR is an impulse radar; it is fully polarimetric operating from 40 to 1040 MHz with a norminal resolution of 15 cm x 15 cm. The BoomSAR, when fully extended, stands 150 feet tall and collects backscattered data from targets typically located at 150-600 feet in ground range.

2.2 Site

The Phillips Drop Zone (PDZ) at YPG was chosen to be the primary site for the 1995 Yuma GPEN experiment. Figure 2 shows a photo of the PDZ area. PDZ is about 1.5 km long and 800 m wide, and it is surrounded by natural desert vegetation and terrain. Soil sample measurements have revealed a large variability in soil electrical properties [7].

Target deployments were either in or around PDZ (Figure 3) [8]. Other targets were deployed at the Cibola Range and Lechuguilla Desert at YPG.

2.3 Targets

There were three primary target categories: tactical targets, environmental and communication related targets, and calibration targets. The tactical targets included military vehicles, ammunition boxes, missile clones, and a minefield. The environmental and communication-related targets included pipes, communication wires, and cables. The calibration targets included trihedral corner reflectors, dihedral corner reflectors, and spheres; these targets were used for SAR focusing, and for polarimetric radar calibration.

The minefield was located east of the Boom road, near its north end. Figure 4 shows the layout of the minefield, which consisted of anti-tank mines and Valmara-69 anti-personnel mine clones. (All without explosive)

3. Results and Discussion

The majority of the processing and analysis effort to date has used data collected using the Folpen III and BoomSAR systems. The following subsections, present results derived from data collected using these two systems.

3.1 Raw Data and RFI

The Raw data collected by the Folpen III system exhibits significant radio frequency interference (RFI) in the 200-400 MHz band (Figure 5). This RFI must be filtered out in order to achieve sufficient sensitivity to image buried targets. An adaptive RFI mitigation algorithm was developed by MIT/LL. This algorithm estimates the RFI spectrum from the pre-nadir signal and subtracts it from the spectrum of the post-nadir signal. Figure 6 shows an RFI-mitigated spectrum of the signal shown in Figure 5. A visual comparison of the figures shows that the algorithm has reduced the spikiness of the spectrum. The algorithm has been sucessfully tested and is currently being used in the image production.

3.2 SAR Images and Analysis

Figure 7 shows a Folpen III image of the PZD. Near range is at the bottom of the image. The narrow bright strip near the bottom of the image indicates the nadir return. This image was generated from 200-400 MHz data, with a 30^o integration angle, 1 m x 1 m resolution, and HH polarization. The area on the ground represented by this image is roughly 1.5 km in cross range and 0.6 km in range. Images of the two metallic buildings, shown in Figures 2 and 3, appear at the upper left corner. These metallic buildings have large radar cross sections (RCS), and apparently cause a significant imaging artifact in the vehicle area portion of the image. The strength of this imaging artifact could be reduced by applying appropriate cross-range weighting.

Data collected from the trihedral array near the center of Figure 7 is used for calibration. The calibration procedure involves setting proper RCS values and compensating for antenna pattern. Figure 8 shows the clutter distribution derived from the

calibrated image. The mean and median clutter levels are about -19 dBsm/pixel and -24 dBsm/pixel, respectively. The long tail of the clutter distribution is caused by the man-made objects and clutter discrete such as cacti and large bushes. Median background level in PDZ is comparable to the median clutter level measured at 1993 Yuma site [1,2]. (The noise level of the Folpen III system is still being investigated.)

Figure 9 shows an enlarged image of the wire/pipe deployment area, extracted from Figure 7. Ground truth for this area was reported in reference [8]. The linear signatures that are seen at approximately 15° angle with respect to the flight path correspond to some of the wire/pipe deployments. One segment of these signatures corresponds to a 50-cm-deep 0.5 in diameter metallic pipe, and has approximately 5 dB T/C. Also shown in Figure 9 is the missile clone deployment area (lower right corner). Both the surface and the 50-cm-deep missile clones are visible, and have greater than 15 dB T/C.

Figure 10 shows an enlarged image of the minefield (Figure 4) deployment area extracted from the image in Figure 7. The depression angle at the minefield is approximately 40°. The minefield contains three different types of metallic anti-tank mines, as well as the M-80 plastic anti-tank mines and the metallic portion of Valmara-69 anti-personnel mines. The M-80 mines are not visible. The surface metallic mines have approximately 12 dB T/C. Most of the metallic mines, that are buried just below the surface, are visible and have approximately 8 dB T/C. Some of the deeper buried metallic mines are also visible. Individual Valmara-69 are too small to be seen in a 1 m x 1 m resolution image; what is visible, however, is the signature of the trip wire that connects the Valmara-69 mines.

Figure 11 shows a BoomSAR image of the minefield. This image was processed by ARL in near real time. This image is not fully calibrated; it corresponds to VV polarization, 35° depression angle at the near range, 25° at the far range, and 15 cm x 15 cm resolution. The background is approximately -39 dBsm/pixel. The low clutter RCS per pixel is primarily due to the achieved high resolution. Using Figure 11, we can identify some metallic anti-tank mines that are not distinguishable in Figure 10. The T/C of the surface mines is approximately 16 dB, and the T/C of the buried mines is approximately 12 dB. The 2-4 dB higher in T/C measured in this image compared with the measurements from the Folpen III image in Figure 10 may attributed to the VV polarization near Brewster angle. Figure 12 shows an enlarged BoomSAR image of the Valmara-69 deployment area extracted from Figure 11. Note, because of the VV polarization, the connecting trip wire is not visible, but because of high resolution, individual Valmara-69 mines are visible.

4. Summary

A second significant ground penetration experiment has been conducted by MIT/LL and ARL in PDZ at Yuma proving ground, AZ. Three radars collected SAR data on variety of surface and buried targets. These radars were the SRI Folpen III, the ARL BoomSAR, and the Navy P-3. Ground truth data were documented. Preliminary data processing efforts have been concentrated on data collected using the Folpen III and the BoomSAR systems.

The Folpen III system covered the 200-400 MHz band with dual co-polarized channels. High resolution imagery was processed. A preliminary clutter distribution of PDZ was calculated and found comparable to that of the 1993 Yuma site. Raw data revealed significant RFI. An adaptive RFI mitigation algorithm was developed and used effectively. Surface and buried targets, including mines, wires/pipes, and missile clones are identified in the imagery.

The BoomSAR covered the 40-1040 MHz band and was fully polarimetric. Ultra high resolution imagery (15 cm x 15 cm) were processed by ARL. Preliminary BoomSAR imagery revealed the potential of detecting small partially metallic anti-personnel mines, the Valmara-69 mines, which have not yet been visible in 1 m x 1 m resolution imagery.

Acknowledgment

This work was sponsored by the U.S. Army Research Laboratory as the executing agency for the DIA/Central MASINT Office Ground Penetrating Radar Program, under Air Force Contract No. F19628-95-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.

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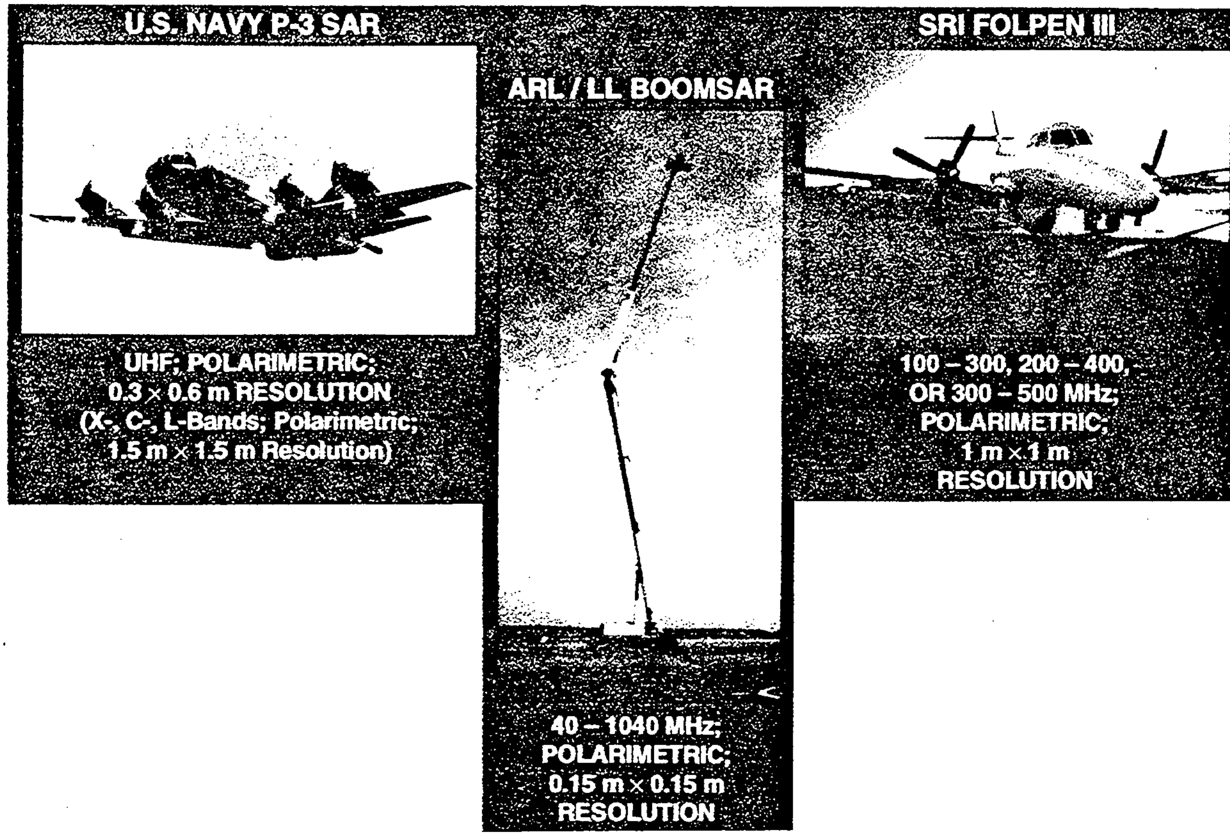

Figure 1: SARs used in the 1995 Yuma experiment.

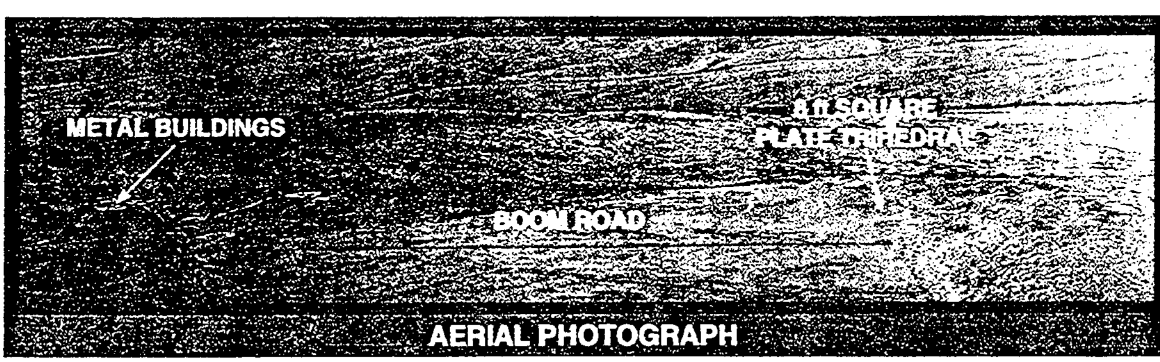

Figure 2: Aerial photo of Phillips Drop Zone.

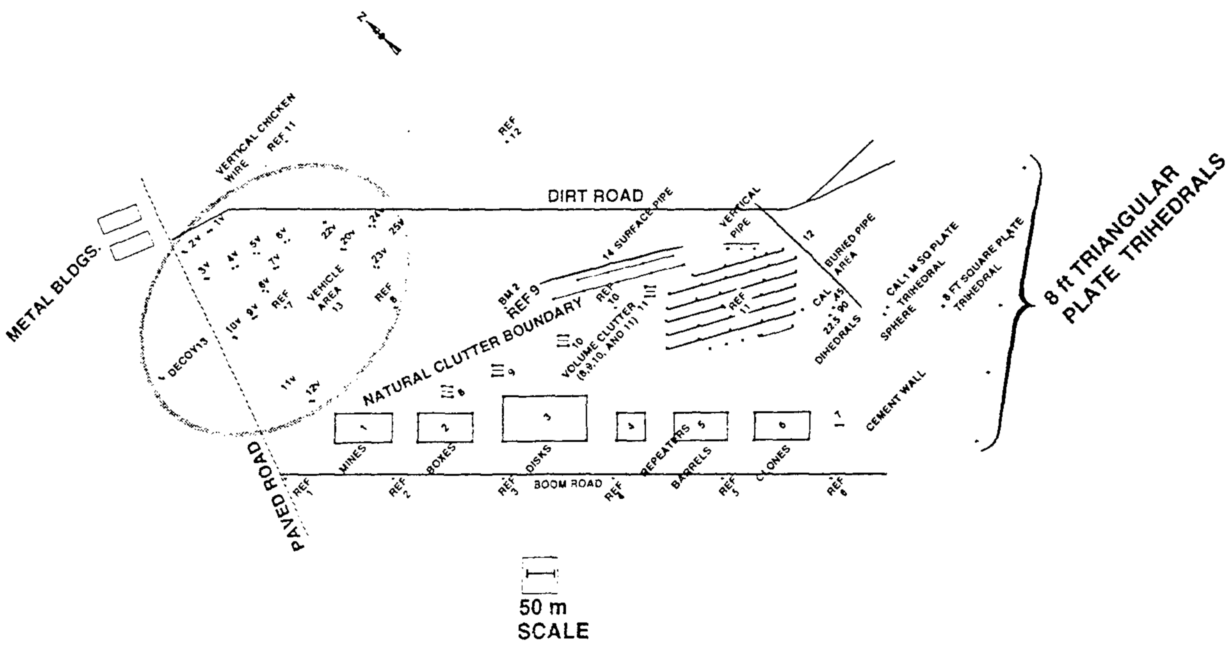

Figure 3: Target layout in or arround Phillips Drop Zone.

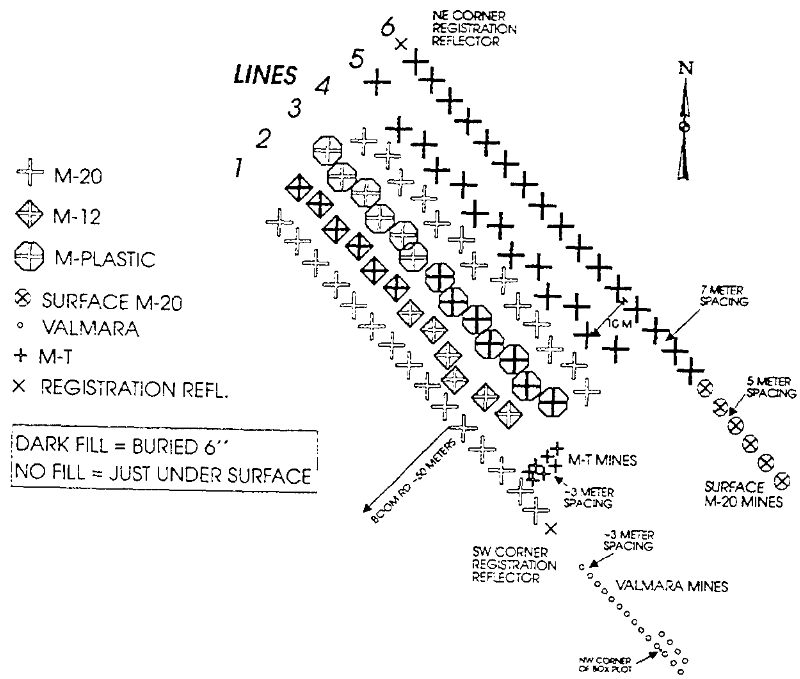

Figure 4: Detail layout of the minefield.

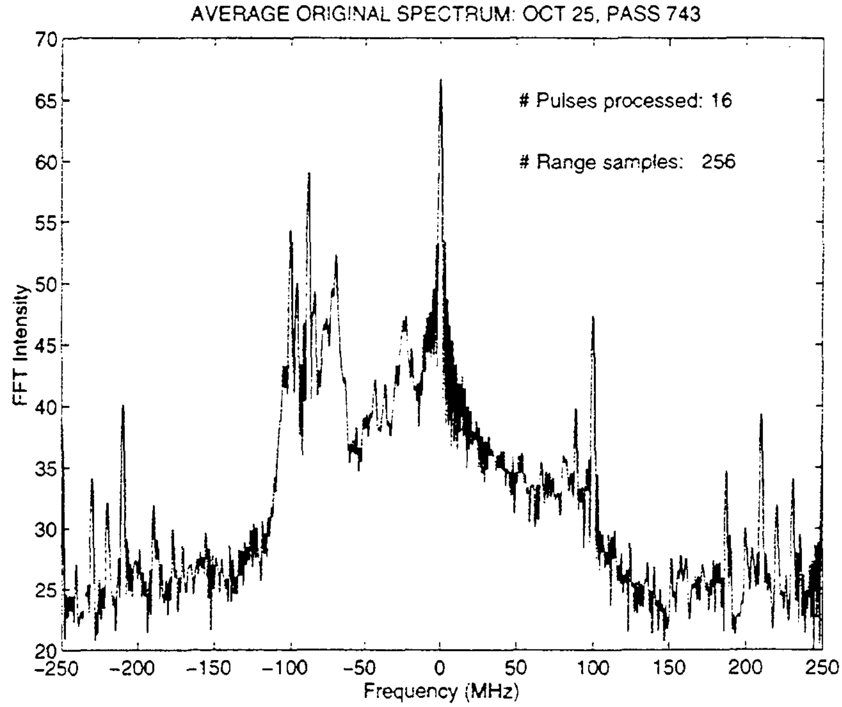

Figure 5: Frequency spectrum of a raw data, SRI Folpen III, 200-400 MHz, HH.

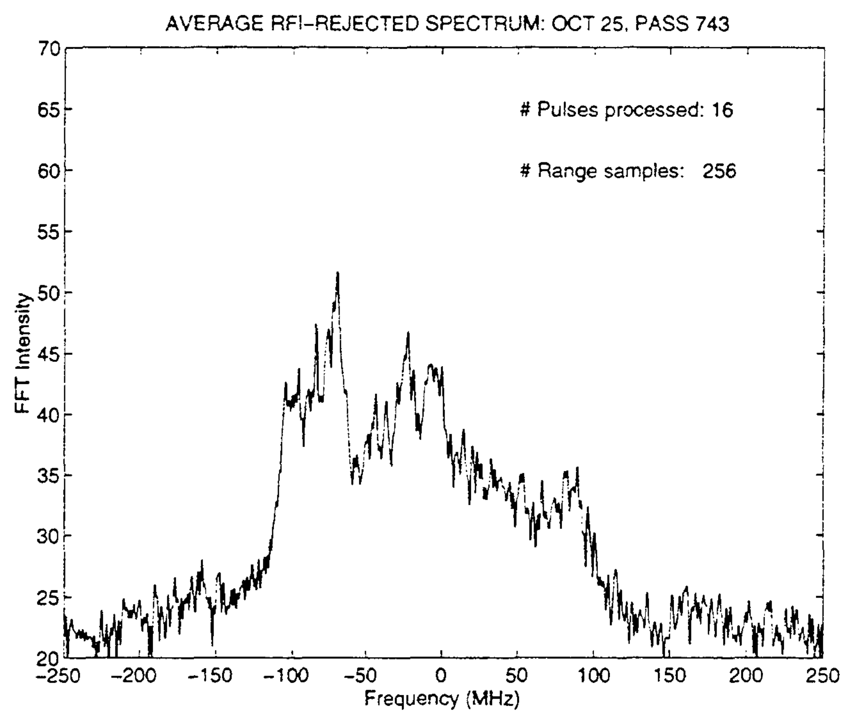

Figure 6: RFI mitigated frequency spectrum, SRI Folpen III, 200-400 MHz, HH.

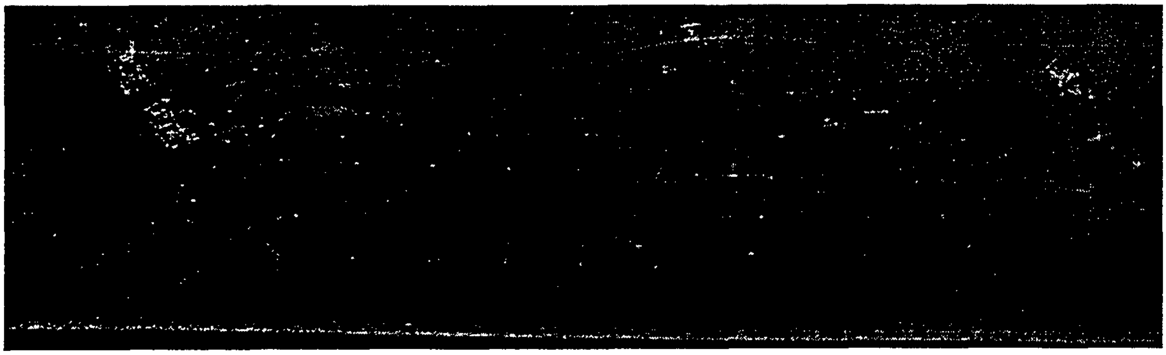

Figure 7: SRI Folpen III image of Yuma−95 site in PDZ YPG AZ, HH, 200 − 400 MHz, 1 m x 1 m resolution.

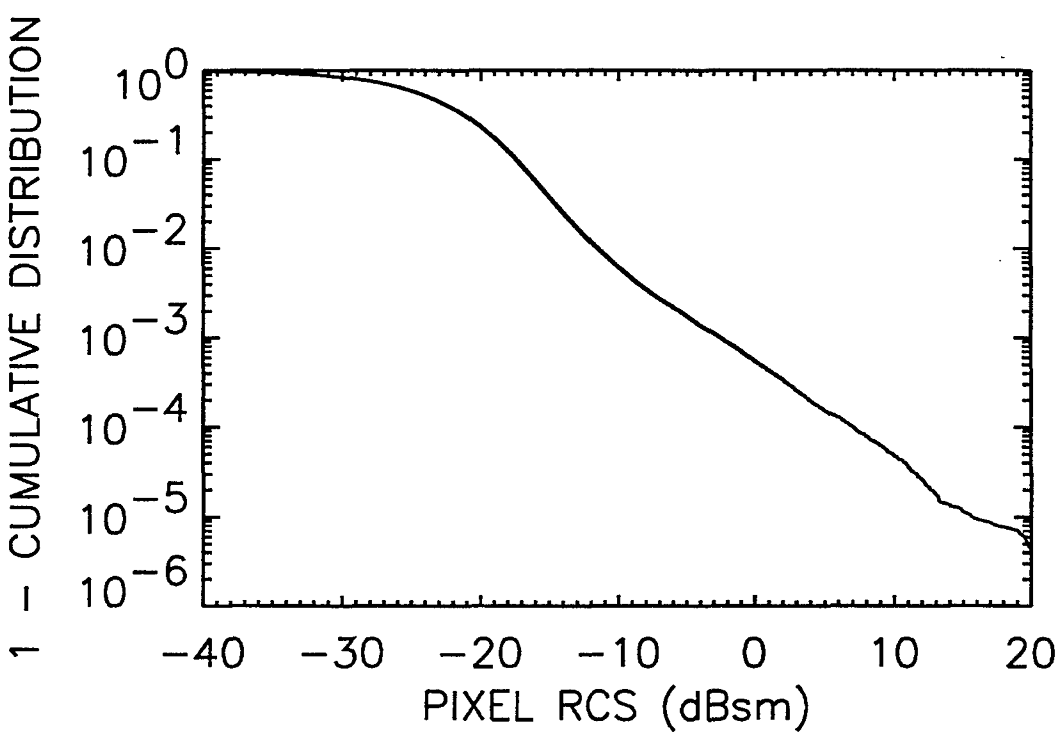

Figure 8: Clutter statistics, SRI Folpen III, PDZ YPG AZ, Yuma−95, HH, 200 − 400 MHz, 1 m x 1 m resolution.

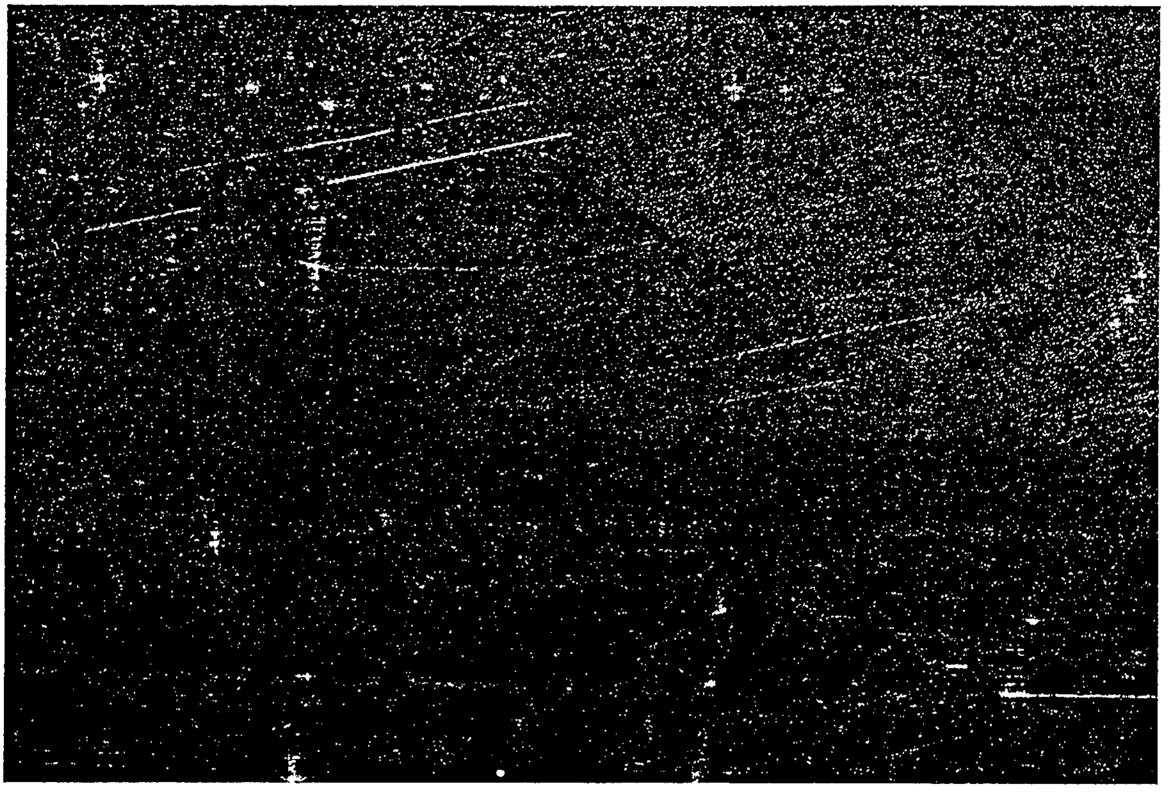

Figure 9: SRI Folpen III image of wire/pipe/cable site in PDZ YPG AZ, 200 – 400 MHz, 1 m x 1 m resolution, HH, Yuma–95.

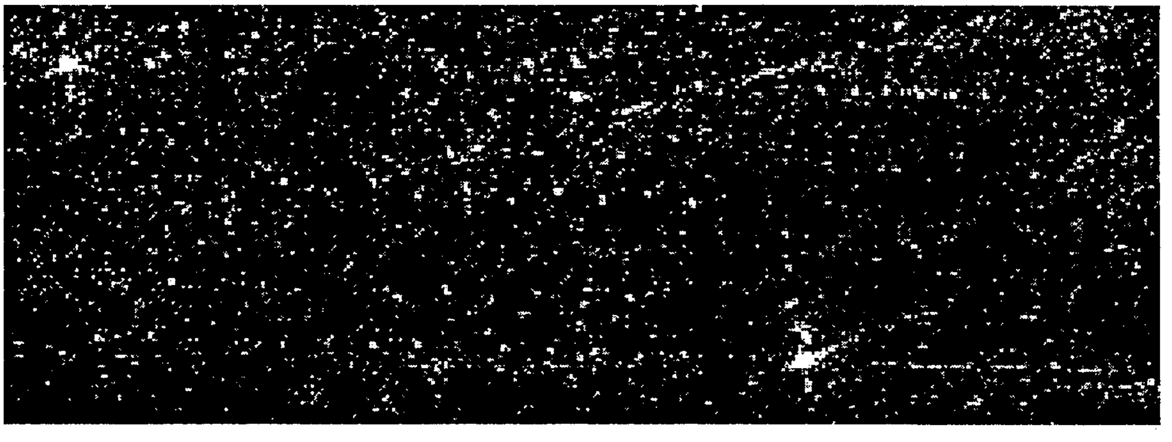

Figure 10: SRI Folpen III image of a minefield in PDZ YPG AZ, 200–400 MHz, 1 m x 1 m resolution, HH, Yuma–95.

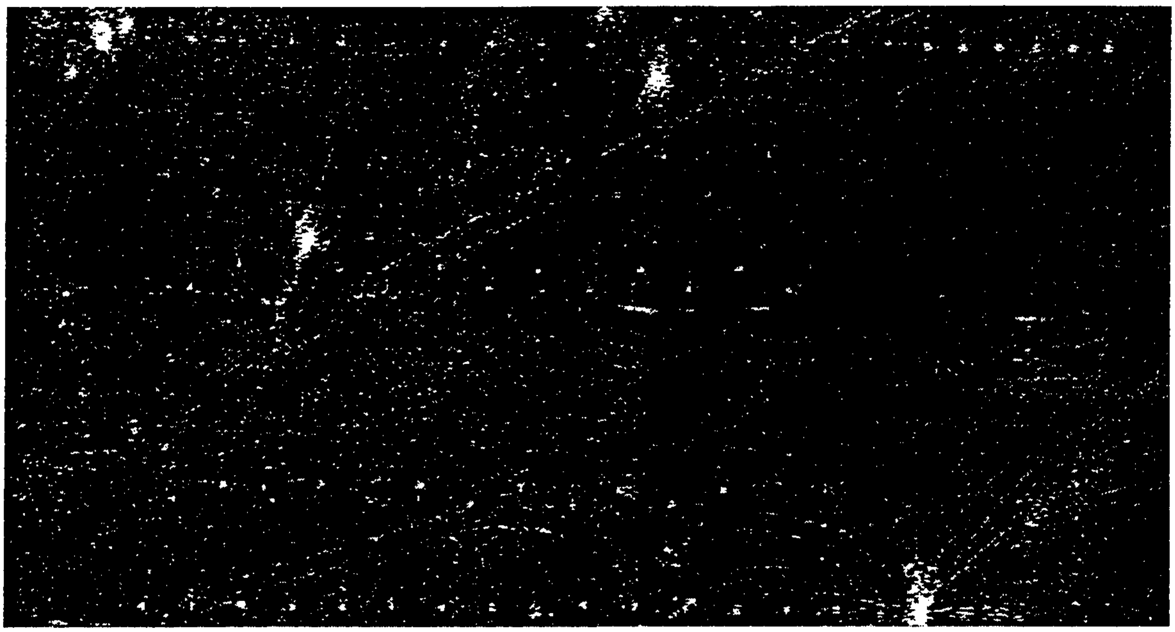

Figure 11: BoomSAR image of minefield in PDZ YPG AZ, W, Yuma–95, 15 cm x 15 cm resolution.

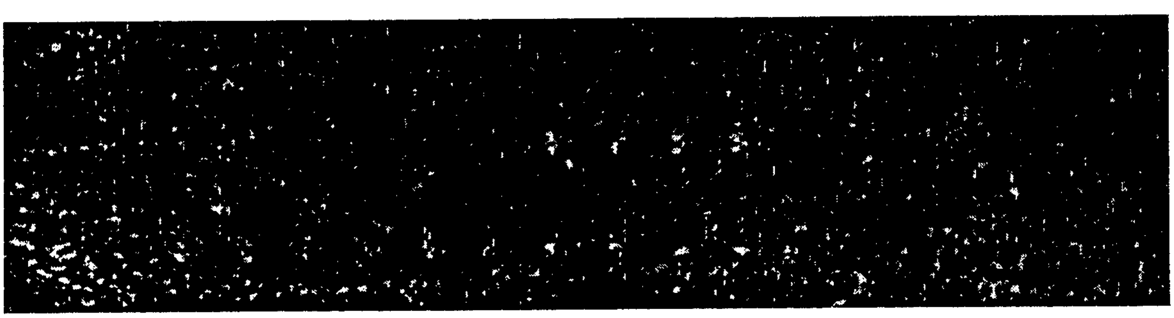

Figure 12: BoomSAR image of Valmara–69 mines in PDZ YPG AZ, W, Yuma–95, 15 cm x 15 cm resolution.

FUSED AIRBORNE SENSOR TECHNOLOGY

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ABSTRACT

No rapid (airborne) reconnaissance and survey capability exists to detect, localize, and discriminate buried and partially buried unexploded ordnance (UXO) and ordnance and explosive waste (OEW). In the last decade, several factors point to the need for a new approach in site survey and cleanup methodology including an increasing number of areas being surplused by the Department of Defense (DOD), the continual public awareness of the location and status of formerly used defense sites (FUDS), and the reduction in DOD budgets. The need for a safe, accurate, economical, and time-expedient land survey and detection capability has never been so great.

Fused Airborne Sensor Technology (FAST) is derived from a similar proven multi-sensor fusion approach for mine reconnaissance against buried sea mines, the most difficult mines to detect in underwater environments. The FAST concept will use a single helicopter platform for spatial and temporal co-registration and fusion of sensor data. Sensors will include a superconducting magnetic field gradiometer, a two-color infrared camera, ground-penetrating radar, and a visible spectrum camera. The combination of these sensors allows for detection, identification, and localization of a wide spectrum of targets. Multiple "looks" at the target and associated clutter by sensors detecting differing physical phenomena will allow lowering individual sensor thresholds to ensure each sensor detects all targets and clutter of interest. Sensor fusion will then be used to reject the clutter. Since sensor characteristic information is derivable through testing for both targets of interest and known clutter, a "fingerprinting" process can be used to pull the targets from the typically clutter-rich background.

The FAST concept will be presented with sensor and fusion methodology for application to a wide variety of buried and partially buried targets.

BACKGROUND

No rapid (airborne) reconnaissance and survey capability exists to detect, localize, and discriminate buried and partially buried unexploded ordnance (UXO) and ordnance and explosive waste (OEW). In the last decade, several factors point to the need for a new approach in site survey and cleanup methodology including an increasing number of areas being surplused by the Department of Defense (DOD), the continual public awareness of the location and status of formerly used defense sites, and the reduction in DOD budgets. Before public lands can be made available for private use, the presence of hazardous materials must be evaluated; if detected, remedial actions may be necessary. The time-consuming, tedious, labor-intensive site characterization and survey process currently used is totally inadequate to provide useful information for strategic planning and prioritization of the vast areas (millions of acres) of land in reclamation efforts under consideration. Sensors capable of detecting UXO and other potentially hazardous material, deployed from an airborne platform will reduce the associated costs and schedules for both survey and remedial actions. The combination of information fusion from multiple sensors with existing sensor technology will permit development of an airborne capability today; the need for a safe, accurate, economical, and time-expedient land survey and detection capability has never been so great.

FUSED AIRBORNE SENSOR TECHNOLOGY (FAST) CONCEPT

The FAST concept for airborne survey and detection of UXO is derived from a multi-sensor fusion approach for mine reconnaissance and against buried sea mines, the most difficult mines to detect in underwater environments. For buried sea mines, a triad of sensors (superconducting magnetic field gradiometer, synthetic aperture sonar, and side-scan sonar) were used in the Magnetic and Acoustic Detection of Mines (MADOM) system to provide

independent and complementary "looks" at the targets (buried sea mines) and associated clutter (non-mines). Through fusion of the data, more than 98 percent of the clutter targets was eliminated. This approach is not being developed for waterborne UXO as part of the Mobile Undersea Debris Survey System (MUDSS) in support of the Strategic Environmental Research and Development Program (SERDP) (Reference 1). The MUDSS program is fusing three sonars, a superconducting gradiometer, a laser line-scan electro-optic sensor, and a chemical analyzer into a single platform sensor suite. With the proper sensor suite, a similar fusion approach is directly applicable to the airborne detection of buried and partially buried land-borne targets and the subsequent rejection of the benign debris, thus reducing false alarms, cost, and time.

A rapid helicopter survey capability which could quickly assess areas for high/medium/low/no explosive ordnance occurrence would provide great utility for rapid land reclamation for residential, industrial, and public uses. The conceptual sensor suite for the FAST system will provide capability to detect buried targets and reject clutter by employing selected sensors which exploit different physical detection mechanisms to detect both UXO and target background clutter. The specific FAST concept presented here is the product of joint intellectual conceptualization of a government and private sector team. The team members include:

- The Coastal Systems Station (CSS), Dahlgren Division, Naval Surface Warfare Center

- Stanford Research Institute (SRI) International

- Lockheed-Martin, Baltimore, MD

- Loral Federal Systems, Manassas, VA.

The FAST sensor suite includes:

- A CSS superconducting magnetic field gradiometer which will be used to locate *ferrous* targets and clutter. This sophisticated sensor provides critical range and bearing information and detailed magnetic moment identification.

- A Stanford Research Institute (SRI) International ultra-wide-band ground-penetrating radar (GPR) which will be used in either the synthetic aperture or depth profiling mode to detect radar scattering associated with *conductivity* effects manifested in surface and buried targets and clutter.

- A Lockheed-Martin two-color infrared camera will be used to distinguish *thermal* mass signatures of buried and partially buried targets and clutter from normal surface background.

- A commercial-off-the-shelf (COTS) *visible* multi-spectral camera will provide coverage from visible to near infrared, to reject surface clutter and correlate location. A COTS global positioning system (GPS) and a laser altimeter will be used for localization. Each of these sensors (Figure 1) has demonstrated airborne capability, but has never been integrated into a single helicopter platform for UXO detection. The platform and sensor suite integration will be accomplished by Loral with experience in helicopter sensor suite integration, especially with magnetic sensors. The entire team will provide expertise in sensor signal processing and data fusion.

An artist concept of the FAST system is shown in Figure 2, depicting a section of land for survey, example targets of interest, the helicopter and towed sensor suite, and the swath paths for individual sensors. The FAST system will provide for overlapping coverage for each of the four sensors to provide multiple "looks" at both the targets and clutter with both temporal and spatial co-registration. The superconducting gradiometer will be towed under the helicopter at an altitude of approximately 30 feet above the ground; the swept path of the gradiometer is spherical in shape with the sensor at the center of the sphere and detecting ferrous objects below the surface. The swept path of the ground-penetrating radar is shown in both the depth profiling mode as a disc-like shape penetrating below the ground surface, and the synthetic aperture mode to the side of the helicopter, also reaching below the surface. Either of the GPR modes could be selected in the FAST system; the synthetic aperture mode might be utilized for initial site survey at higher altitudes while the depth profile mode would be used for detailed survey. The swept paths of both the two-color infrared sensor and the visible spectrum camera are depicted as overlapping planes to again provide spatial and temporal co-registration. The infrared sensor would provide some capability against buried targets and clutter whose thermal mass provides a surface signature; the visible camera provides information for surface targets and clutter and location correlation.

TARGET DETECTION AND CLUTTER REJECTION

The detection of UXO in either a waterborne or land-borne environment is a difficult task that is closely associated with the mine reconnaissance and identification problem. Several factors make the mine detection problem difficult including the varying environmental conditions, extent of burial time constraints and differing mine materials, size, and shape. The detection of UXO is even more challenging when considering the additional factors of aged targets in the environment, the large number of targets, widely varying environmental conditions, and the small target sizes of typical UXO. Sensor combinations are needed that have the joint capability to 1) provide high probability of detection for targets and 2) effectively remove background man-made or environmental clutter. UXO targets have widely varying geometry, mass, and material differences (i.e., targets include small 60-mm mortar rounds to the much larger 2000-pound bombs). These UXO targets must be "fingerprinted" by the sensor suite to be identifiable from difficult background environments (characterized by surface debris, vegetation, and rugged terrain) that also contain clutter or false targets, such as ferrous (i.e., cans and rods) and conducting (i.e., sheet metal and wire) anomalies.

In the case of the buried sea-mine MADOM program, when a single magnetic sensor was used to survey an area of interest, many hundreds of potential targets (mines and clutter) were identified. Similarly, the acoustic sensor alone made hundreds of contacts when surveying the same area. However, when the target information was fused and targets were required to be spatially correlated and exhibit both acoustic and magnetic mine-like qualities, clutter targets were easily identified, thus reducing the number of mine-like targets of interest to literally three or four targets of interest -- the number of potential clutter and real targets was reduced by two orders of magnitude. A seemingly overwhelming problem for individual sensors had suddenly been made tractable through sensor fusion. The key to this success was to lower the sensor detection thresholds so that very few real targets of interest would be missed. This, in turn, results in the adverse effect of increasing the number of clutter contacts, however, it is essential that target probability of detection be maximized. Clutter is rejected by requiring that spatially correlated contact exhibit mine-like qualities in the sensor combination. Implicit to the success of this approach is the necessity to accurately localize and separate (spatial co-registration) individual targets with each sensor. Errors in co-registration can actually complicate the problem by introducing false contacts. It is also critical to note that since detailed target information (shape, size, material) is known for the targets of interest, sensor characteristics for each target can be developed and exploited in the fusion process much like "fingerprints". The ability to discriminate individual target characteristics gives rise to the enhanced value of the sensor with greater sensitivity, fidelity, and dynamic range to provide more information for the fusion process.

For the FAST sensor suite discussed above, four sensors were selected that focus on uniquely different-sensed physical phenomena and proportionalities (see Table 1). The superconducting gradiometer senses shape, orientation, and size of ferrous mass, and is processed to provide target location. The ground-penetrating radar senses radar cross-section, based on conductivity, surface area, and shape. The two-color infrared sensor will sense thermal mass differences that exist at the ground surface which are functions of target volume and size and time of day. The visible camera identifies visible size and shape and location of the surface targets. Again, since the size, shape, and material properties are known for the UXO (and also some of the typical clutter) targets of interest, sensor "fingerprints" can be developed. Individual sensor thresholds are lowered to detect all targets; spatially correlated sensor contacts are mapped; all correlated detections are compared with known "fingerprint" data for each sensor thereby rejecting clutter targets (false alarms) through sensor fusion. This is in contrast to the procedure used with a single sensor where sensor thresholds are raised to limit the number of detections and false alarms to a manageable number, thereby omitting key targets of interest (essentially discarding valuable decision information). Advanced sensor fusion methods are even more sophisticated in their ability to classify an object from a great many features derived from sensor data and multiple "looks". Some of the better methods include Bayesian Probability Networks, Neural Networks, Fuzzy Logic Classifiers, and Expert Systems. Multi-sensor fusion will permit the utilization of all possible sensory information that can be obtained for the targets of interest. Further investigation of Table 1 also identifies that three of these sensors provide some capability against shallow buried targets in the burial depth ranges (surface to 10 feet) of most interest in land-borne UXO.

TECHNICAL APPROACH AND RISK

A rapid demonstration of the FAST concept could be achieved by utilizing and leveraging existing sensor and processing technology developed by the Navy and other agencies in combination with COTS equipment. Existing

sensors and COTS equipment would be assembled and integrated aboard a helicopter platform. The sensor suite would then be exercised to demonstrate capability to detect. localize, and identify buried and partially buried UXO and OEW.

FAST can be demonstratec in a two-year effort. The first year would focus on feasibility and proof of concept for sensors and processing algorithms at a known test site where ground-truth data can be gathered. During the second year, an operational capability would be demonstrated at an actual test site of opportunity. The government, industry team provides a partnership which will ensure a rapid transition of the FAST concept to an operational capability.

Two primary areas of technical risk are readily observable. Operating the gradiometer in close proximity to the ground-penetrating radar is expected to produce interference during the GPR broadcast; careful management of sensor positions will keep the gradiometer out of the main GPR beams and side lobes. Achieving good sensor performance over a wide variety of soil types, clutter densities and types, degrees of surface wetness, and times of day is also a key area of concern. During all system testing and any sensor simulations, performance boundaries would be defined for acceptable FAST system performance. This last area of concern can be mitigated by the judicious choice of operating periods and operational geometries.

POTENTIAL APPLICATIONS

The potential benefits of the FAST concept demonstration are substantial. Significant resources are currently being utilized for FUDS and BRAC reclamation projects. The FAST system concept would rapidly make much needed strategic site survey data available to DOD for transition planning. In addition, the airborne survey method will reduce the time andassociated costs of the survey process and enhance the potential for more rapid return of government land to the public sector. Once developed into a system, the Corps of Engineers would find FAST to be a valuable tool in site survey and subsequent remediation cleanup efforts. The Environmental Protection Agency could utilize FAST as a valuable tool to evaluate remediation to standards for those sites where remedial actions have been pursued.

Hazards to both DOD and private sector personnel could be reduced through the use of the FAST concept by identifying dangerous targets via an airborne platform vice a hand-held or overland, manned approach. Other potential government uses include range cleanup, land mine countermeasures, demining, detection of tunnels used for illegal immigration, detection of illegal underground drug facilities, and detection of weapon stores and facilities.

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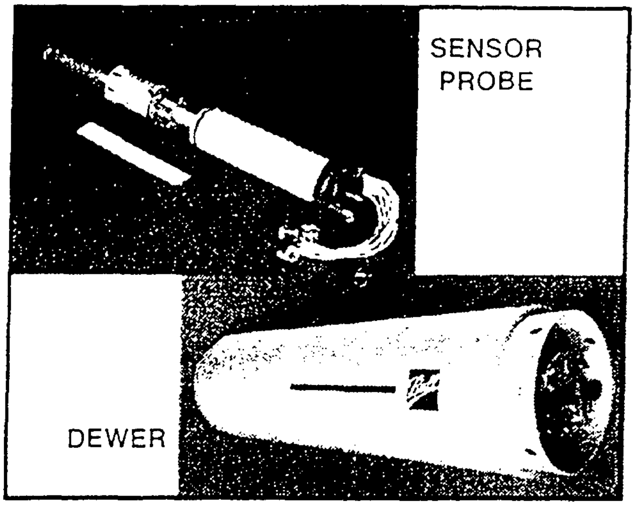
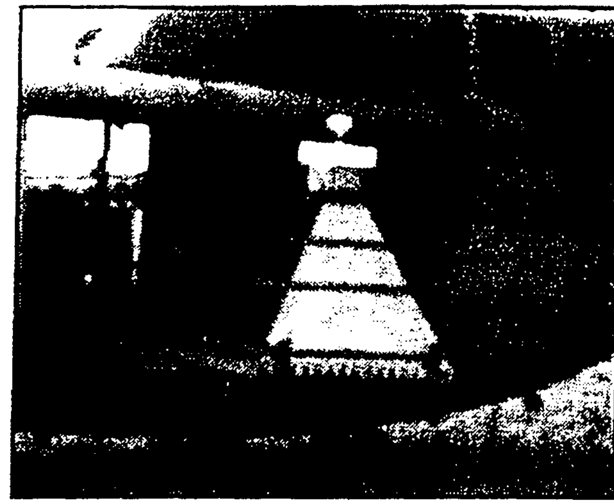
SUPERCONDUCTING GRADIOMETER



GROUND PENETRATING RADAR



DUAL-FREQUENCY IR CAMERA

VISIBLE BAND CAMERA

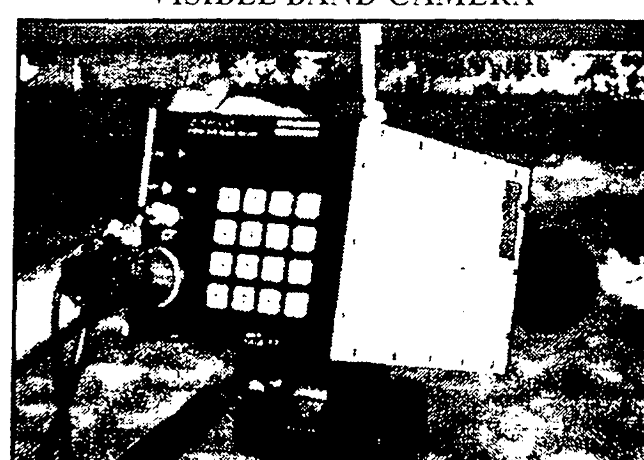


FIGURE 1. FAST SENSORS

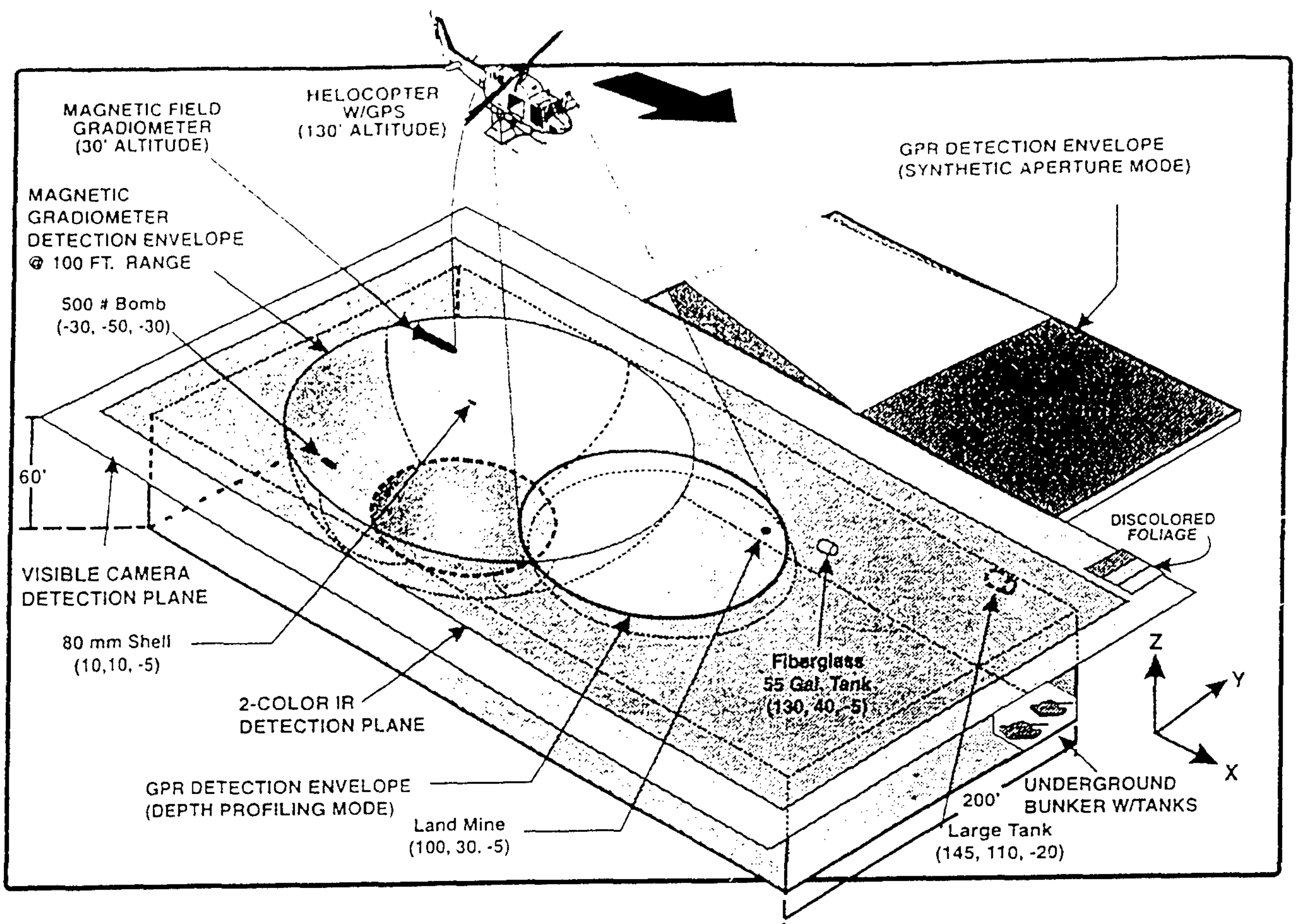


FIGURE 2. FAST CONCEPT

TARGET CHARACTERISTICS & SENSOR CAPABILITIES TABLE

	SENSOR SENSED PHENOMENA (PROPORTIONALLY) / TARGET DEPTH/CHARACTERISTICS)	MAGNETIC FERROUS MASS (VOLUME/SIZE)	GPR RADAR X-SECTION (SURFACE AREA/ SHAPE)	INFRARED THERMAL MASS (VOLUME/SIZE)	VISIBLE SIZE/SHAPE (SURFACE AREA/ SHAPE)
	ON SURFACE (OPEN AREA)	X	X	X	X
	ON SURFACE (UNDER FOLIAGE)	X	X		
AREA OF EMPHASIS	SHALLOW BURIAL (0-2 FEET)	X	X	X	
	MID-BURIAL (2 - 10 FEET)	X	X		
	DEEP BURIAL (>10 FEET)	X			

FAST SYSTEMS APPROACH

- LOWER SENSOR THRESHOLDS TO DETECT ALL TARGETS
- DETECT/IDENTIFY TARGETS VIA KNOWN FINGERPRINTS
- REJECT CLUTTER (FALSE ALARMS) VIA SENSOR FUSION

TABLE 1. FUSED DETECTION CAPABILITY

THE CHALLENGES OF UXO IN THE MARINE ENVIRONMENT

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INTRODUCTION

Many active and former military installations have ordnance ranges and training areas that include adjacent water environments such as ponds, lakes, rivers, estuaries, and coastal ocean areas. War activities, dumping, and accidents have also generated significant unexploded ordnance (UXO) contamination in the coastal waters here in the United States and abroad. Everyday, commercial fisherman are recovering ordnance from the waters off the coasts of Europe. The recovery of underwater ordnance by commercial fishermen overseas is so routine, that they can often identify the make and model of the ordnance in their report. It has also been alleged that commercial fishermen off England will stockpile ordnance in shallow waters to collect a bounty later, when fishing income seasonally falls off. The European Union is again reconsidering the clean up of coastal water, 10 years after deciding the costs were too prohibitive.

While the costs/benefits of underwater UXO remediation are not always clear, limited efforts are taking place within the continental United States (CONUS). In the United States, Naval Explosive Ordnance Disposal (EOD) technicians are uniquely trained to respond to UXO "below the high water mark". This paper discusses U.S. Navy (USN) EOD responsibilities, policies and limitations towards meeting the challenges presented by underwater UXO contamination. The author appreciates the assistance provided by CDR Linnenmann, Royal Danish Navy EOD, Lt. Andy Woollven, Royal Navy, and the Navy EOD personnel of COMEOD Group One (California), COMEOD Group Two (Virginia), Naval School Explosive Ordnance Disposal (Maryland), Fleet Liaison Unit (Maryland), EOD Mobile Unit Two (Virginia), EOD Mobile Unit Six (South Carolina), and EOD Detachment Earle (New Jersey).

A GLOBAL PROBLEM

It was recently reported that the British Ministry of Defence no longer had records of where over one million tons of munitions and weapons were dumped at sea between 1945 and 1963 (*Ocean News and Technology*, 1995). British Gas discovered an uncharted dump site in the path of a planned pipeline intended to connect Scotland with Northern Ireland. The issue of the dump site has reached both houses of Parliament and preliminary efforts are underway to perform some clearance using remotely operated vehicles (ROV's). The Finnish Environmental Minister has recently asked for an investigation of the dumping of munitions at sea by their Defence ministry. Denmark estimates that they have over 300,000 tons of ordnance in dumps off their coast, primarily German war material that is under various stages of degradation. Denmark has two major bridge constructions underway. At one site alone, over 200 World War II mines were discovered. Both England and Denmark have significant quantities of chemical munitions in waters off their coasts. Many other countries, especially those in the Pacific, have had to deal with conventional UXO in their harbors and fishing grounds.

The problem of underwater UXO contamination has commanded more attention with island and coastal nations overseas than in the United States for a number of reasons. First, their ratio of underwater land area under economic control to surface land area is higher, so the sea floor represents a proportionally greater resource. Next, much wartime activity was directed at stopping sea commerce; consequently, significant UXO contamination is located in important areas such as harbors and channels. Finally, marine technology has advanced to allow access to deeper waters. On the other hand, much of the U.S. underwater contamination has occurred near military practice and test ranges. Bombing ranges tend to be remotely located so that there has been minimal direct economic impact. Thus clean up efforts at Formerly Used Defense (FUD) sites have typically ended at the water's edge (e.g. Culebra Island, Puerto Rico). But what started out as a remote site 50 years ago, is often no longer the case. The issue of underwater UXO contamination is an increasing public concern. Most of the underwater remediation efforts that have taken place in the U.S. have been conducted by USN EOD forces. But their remediation efforts are usually undertaken on an ad hoc basis and are often limited in scope. USN EOD policy

and responsibilities in meeting the challenges of marine UXO are best understood in context of their force structure and Chief of Naval Operations (CNO) doctrine, as defined by OPNAV Instructions.

U.S. NAVY EOD FORCE STRUCTURE

USN EOD forces (approximately 1300 personnel) are divided into two operational EOD Group Commands. Both Group One (assigned under Commander-in-Chief Pacific Fleet) and Group Two (assigned under Commander-in-Chief Atlantic Fleet) are administratively assigned to the Pacific and Atlantic Fleet Surface Type Commands, as shown in figure 1. EOD Training and Evaluation Units (EODTEU) are assigned to the Groups to provide training on render safe and disposal procedures and conduct fleet evaluations on EOD tools and techniques. Navy Mobile Diving and Salvage Units (MDSU) are under the operational control of the Groups. (MDSU's have no EOD personnel assigned within their organization, but EOD forces will frequently join MDSU forces in cooperative efforts where coordinated ordnance and salvage efforts are necessary.) Both active and Naval Reserve Force (NRF) EOD Mobile Units (EODMU) are subordinate to the Groups. The EODMU's manage geographically dispersed EOD Detachments, the fundamental operational entity within the EOD organization. Detachments typically have 6 to 8 personnel, but larger detachments are established where the work load is greater (e.g. EOD Detachment China Lake has approximately 12 personnel). EODMU's are responsible for the operational readiness of all their subordinate EOD Detachments. There are five types of EOD detachments that are specialized to counter ordnance and four types of detachments equipped to enhance the capabilities of the ordnance response detachments. EOD detachment functions are defined in OPNAVINST 3501.97E of 26 January 1996, Projected Operating Environment and Required Operational Capability. The detachment functions that are related to underwater ordnance are described below:

a. Mobile (MOB) Detachments deploy for fleet operations and are tasked with contingency operations such as range clearance and aircraft recovery.

b. Mine Countermeasures (MCM) Detachments are specialized to locate and neutralize sea mines.

c. Marine Mammal Systems (MMS) Detachments provide a special capability to detect and neutralize sea mines.

d. Shore Based (Shore) Detachments provide shore installations with a continuing need for EOD services, and will respond to EOD incidents within the local area.

e. Ordnance Clearance Detachments (OCD) are NRF that can be used to augment USN EOD forces on a variety of tasks, including range clearance operations.

f. Area Search Detachments (ASD) are deployable teams equipped to conduct sonar search in support of ordnance and salvage operations.

g. Mobile Communications (COMM) Detachments provide field communications in support of EOD operations.

h. Flyaway Recompression Chamber (FARC) Detachments provide USN EOD Forces in remote locations with an on-site recompression chamber.

i. Mine Location and Scoring (ML&S)/Mine Recovery and Scoring (MR&S) Detachments provide a capability to score and recover sea mines at practice ranges.

There are about 80 detachments within the EOD organization. Whether they could be utilized for underwater ordnance operations is determined by their mission responsibilities as defined by CNO doctrine.

USN EOD UNDERWATER UXO RESPONSIBILITIES

The **primary** mission of EOD forces is to eliminate the hazards from ordnance that jeopardize operations conducted in support of the national military strategy. The war fighting context to the EOD mission constrains the resources available for non emergency response and its impact may not be appreciated by those outside the organization. Geographical jurisdictions determine which service is responsible for responding to a particular hazardous UXO incident. The USN EOD's area of responsibility is defined in OPNAVINST 8027.1G of 14 February 1992, Interservice Responsibilities for Explosive Ordnance Disposal, to include Navy installations and ordnance below the high water mark. (U.S. Army EOD forces have the jurisdiction over ordnance above the high water mark, while U.S. Air Force EOD and U.S. Marine Corps EOD forces operate primarily on their respective bases; all these jurisdictions overlap in emergencies, and at times for convenience.) EOD functions include the capability to detect, locate, identify, render safe, recover, field evaluate and dispose of explosive ordnance. The hazardous context for the term "unexploded ordnance" is an important distinction for an EOD response, because not all UXO is considered hazardous. The hazardous state definition generally includes dud-fired ordnance, and munitions that have deteriorated or been damaged so that normal handling procedures are at risk. The hazardous state surprisingly includes deployed "inert" ordnance (e.g. Mk 76 practice bomb), as these items may have intact pyrotechnic spotting charges. UXO in the marine environment would generally be considered hazardous. UXO includes ordnance items that range in sophistication from cannon balls to modern influence-fuzed sea mines. EOD training requires

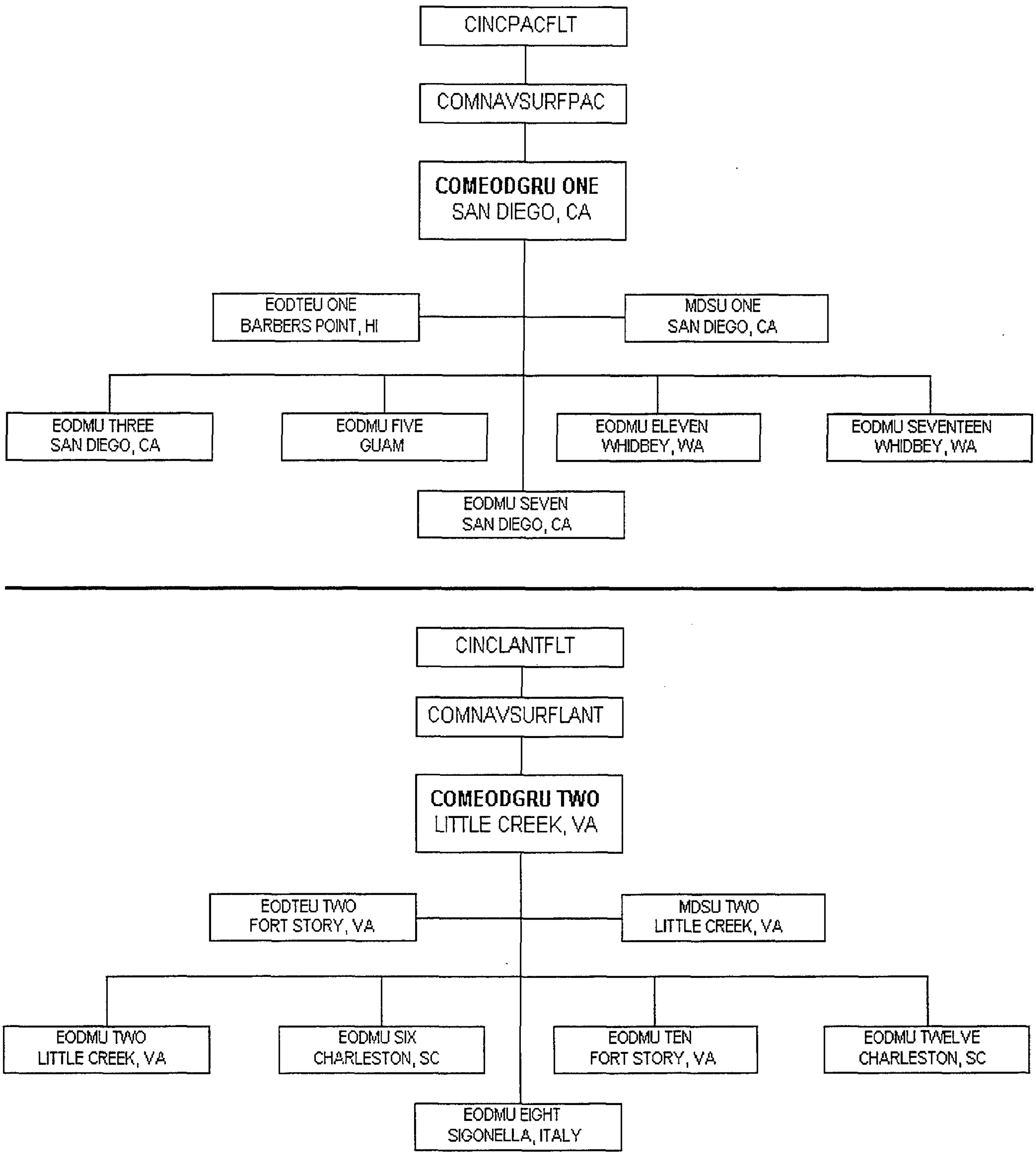

FIGURE 1 EOD OPERATIONAL FORCES

a one man-one ordnance focus so that proper identification, handling, and render safe/neutralization procedures can be accomplished. Situations where there are thousands of UXO about the sea floor are resolved one item at a time.

Demands, placed on USN EOD to maintain a trained combat ready force with a high degree of mobility, influence their ability to respond to "secondary" missions such as "routine" underwater remediation. The peacetime context of OPNAV Instruction 8027.6D of 21 July 1983, Naval Responsibilities for Explosive Ordnance Disposal, obligates the USN EOD to be capable of providing services for (1) public emergency situations that require their expertise, (2) for the clearance of UXO remaining in "former combat zones, training areas and target ranges", and (3) when directed by competent authority as in meeting our nation's obligations. (Note: environmental clean up activities at FUD sites are specifically assigned to the U.S. Army Corps of Engineers (USACE) in OPNAVINST 8027.1G; item (2) above is currently interpreted to mean "active" training areas and target ranges). The above three situations provide the policy guidance for the acceptance of EOD services requests. As a general rule, U.S. military ordnance, a federal agency, or federal property must be involved in the request. Otherwise an explosive device incident (e.g. a homemade pipe bomb in a community pool) will be turned over to proper civilian authorities.

USN EOD UNDERWATER UXO POLICY

The requesting activity and the level of urgency have bearing on the consideration of any EOD services request. Guidelines clearly support the need to maintain public safety by the timeliness of a competent response. Time is often a critical factor, and USN EOD response to UXO incidents in CONUS includes gaining rapid control over any situation so as to minimize loss of life and property. The response policy is further discussed in the emergency, non-emergency, and national need sections that follow.

Emergency Response

In the mid-1960's, the fishing trawler *Snoopy* snagged a World War II German torpedo in her nets off the Grand Banks of New England. Before EOD units could arrive on scene, the crew lifted the torpedo clear of the water. Heavy seas caused the warhead to hit the side of the vessel, and the resulting explosion killed three of the five man crew and sank the vessel. The propeller of the torpedo was recovered and showcased with its story for students at the Naval Explosive Ordnance Disposal School in Indian Head, Maryland. The request for EOD emergency services can be as informal as a phone call or radio message and can be accepted for action at all levels of the EOD organization. Emergency requests can originate with individuals, companies, civil authorities, and the military services. The U.S. Coast Guard generates many requests because they are often the first to be notified of an UXO incident. The level of urgency, jurisdiction/nearest available EOD response unit, and again, the propriety of a military response are all considered, with the paperwork occurring after action.

Non-emergency Response

The policy of USN EOD towards underwater UXO is to remove ordnance that presents a hazard to the public, as tasked. Ordnance that does not present an immediate danger may be left alone. For example, USN EOD declined a request to search for UXO lost near the piers of Charleston Naval Base, a current FUD site. When underwater UXO comes into the public view so as to constitute a public danger, a self-initiated response develops. For example, according to EOD Detachment Earle, Dan Berg published in "Wreck Valley" the location and description of the *USS San Diego* (a World War I ammunition ship sunk 14 miles off the coast of New York). EODMU Two and MDSU Two have now surveyed the wreck, determined that the UXO is still detonable, and are in process of determining how to seal the ship from public access. A problem with USN EOD response policy sometimes develops in "non-emergency" cases. The case of the German submarine U352 illustrates the point. U352 was sunk off the coast of South Carolina in World War II and became popular with sport divers, even though it had live torpedoes on board. Not until 1982, after civilian authorities got congressional attention, did USN EOD remove four external torpedoes and weld the hatch to the internal torpedo locker. Another case history is represented by the 1950 explosion at the Augusta Street Pier on the Raritan River in South Amboy, New Jersey. The explosion involved 60,000 M1A1 anti-tank and M2A4 anti-personnel mines. An initial clean up failed to account for 13,000 mines, most of which were believed to have been consumed in the explosion. A $350 million proposed redevelopment effort in the area raised concerns whether any mines remained. A 1993 investigation located several mines. Although the mines were military ordnance, they were manufactured by a company for export and failed the federal ownership qualification criteria. Only after an interservice agreement was established between the Federal Environmental Protection Agency (EPA) Technical Support Section and USN EOD in 1994, did remediation efforts begin. Remediation efforts in October, 1994 by EOD Detachment Earle located 123 M2A4 mines. Figure 2 shows how corrosion has affected the shape of the mines. The corrosion was removed from the upper left mine that is

right of the pager. Routine EOD services requests from

Figure 2. M2A4 Mines, South Amboy, NJ

activities within the Department of Defense take the form of an "8027 Request". The 8027 Request would identify the services required, location, and funding. Any request for services such as underwater remediation is considered in light of feasibility, resource availability, and the need to maintain mission readiness.

Requests are handled at CINC level, and forwarded to the respective EOD Group. CINCPACFLTINST 8027.1M and CINCLANTFLTINST 8027.3D describe the necessary message format. A good example of USN EOD support of underwater remediation efforts via an 8027 Request is the Camp Lejeune, NC operation. The purpose of the biannual remediation of UXO in the Atlantic Intercoastal Waterway at Camp Lejeune is to reduce the risk to USACE dredging operations. The most recent exercise was completed in November 1995. Approximately 2.3 km of channel was searched by divers using hand held metal detectors; 28 ordnance items were recovered.

National Need

Two of the most significant underwater clearance efforts undertaken by USN EOD forces took place overseas in the Suez Canal (1974) and Kuwait port waters (1991). Both operations were conducted to honor U.S. commitments made to foreign governments. The Suez Canal operation involved searching a 200 km channel for underwater UXO. The search for UXO included the use of divers and boats towing sonar and magnetometers (Burdette and Rice, 1974). Approximately 60 tons of ordnance and munitions were recovered and disposed. The operation eventually led to the establishment of the Area Search Detachments within the EOD organization. The clearance of Kuwait's five ports required USN and allied EOD diver to search 1200 hectares of sea floor with hand held sonars for Iraqi sea mines and other UXO. Over 80 tons of ordnance in and around the ports were destroyed (Nagle, 1992). The action for both these missions was initiated at the highest levels of government and coordinated through CNO. Clearly if the tasking for UXO remediation comes from high authority, USN EOD will respond.

OUT OF SIGHT - OUT OF MIND?

The requirements, costs, and effectiveness of underwater UXO remediation must be considered in light of our environmental priorities. Underwater UXO remediation should be considered when the net economic, social and political benefits exceed the costs of doing nothing. It is beyond the scope of this paper to identify the direct and indirect costs involved in this analysis. It is clear that the concerns over underwater UXO are growing, yet the major focus of current UXO remediation efforts, technology development, and technology assessment has largely been directed towards surface UXO contamination. After all, it is intuitive that greater benefits to the public good can be derived at a lower cost for land remediation than for underwater remediation. In the meantime, a not unusual response to underwater UXO contamination is to consider barrier technology that keeps the ordnance in the water. (For example, turtle excluders welded to suction dredges operating off Sandy Hook significantly reduced the number of EOD response calls).

There has not been the general perception of harm from our domestic underwater UXO contamination. Certainly, no activity goes out of their way to publicize underwater UXO incidents, and it is easy to speculate that the sea is quick to bury the unfortunate and hide the evidence. What danger does the corroding 500 pound bomb pose to the diver off Culebra Island in figure 3?

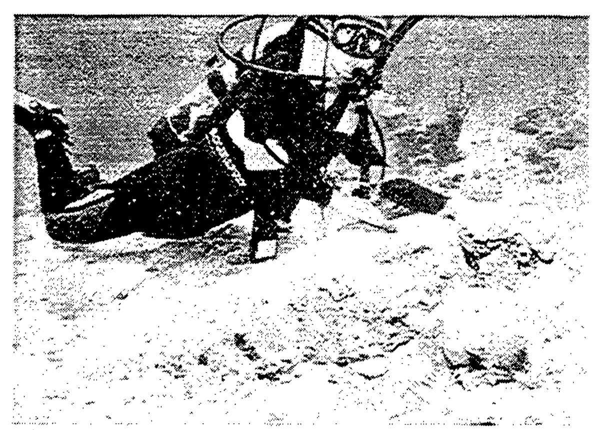

Figure 3. Sport Diver off Culebra Island
photo courtesy of Lt. Daubon

The hope that underwater UXO will just disintegrate and go away has to be tempered. The recovery of King Henry VIII's ship, *Mary Rose*, showed that the sea muds of Portsmouth, England, are capable of preserving metal artifacts quite well for over 5 centuries. The issue of "ordnance fate" in the sea environment is not well studied. EOD procedures have the general cautions of the unknown effects immersion and corrosion can have on ordnance. A U.S. Army manual, TM 9-1300-214, Military Explosives, cautions that torpex, a common underwater explosive, can be shock sensitized by contact with water. Europeans treat German ordnance constructed of "Rhinemetal" with caution, as mines constructed with it show little deterioration after 50 years of immersion.

SUMMARY AND RECOMMENDATIONS

USN EOD performs routine underwater UXO remediation tasks on a limited basis. The criteria for accepting these tasks is strongly influenced by their mission obligations. USN EOD does not have the resources to support the demand for large scale remediation efforts, and, at times, must turn away non-emergency requests for services. Proposals such as EPA's "Munitions Rule" will likely affect the demand for EOD services and will also change the way EOD conducts operations. USN EOD provides a unique and valuable service in meeting the challenges posed by underwater UXO. Their prevalent methodology of using divers as a search and removal platform demands a highly skilled and trained individual. The effectiveness of USN EOD search techniques for (non-mine) UXO has not been adequately documented. EOD diver and ASD performance need to be baselined in a controlled test as was performed by the Naval Facilities Engineering Service Center in Hawaii (Wicklund, 1995). New technologies with improved search effectiveness, such as those under development by the Coastal Systems Stations, Panama City, are needed for more efficient site characterization. Technologies that gets divers out of the water, such as those under investigation by USACE Waterways Experimental Station, MS, and by overseas countries, need to be developed so underwater remediation is safer and more cost effective. Studies on the long term effect of immersion on ordnance are also needed so that proper risk management decisions are made. Finally, there needs to be a centralized accounting of all of our underwater UXO contamination and the accidents that have occurred. The direct and indirect impact of UXO contamination should not remain "out of sight - out of mind".

ABBREVIATIONS

ASD	Area Search Detachment
CINCLANTFLTINST	Commander in Chief Atlantic Fleet Instruction
CINCPACFLTINST	Commander in Chief Pacific Fleet Instruction
CNO	Chief of Naval Operations
EOD	Explosive Ordnance Disposal
EODMU	EOD Mobile Unit
EPA	Environmental Protection Agency
FUD	Formerly Used Defense
MDSU	Mobile Diving and Salvage Unit
NRF	Naval Reserve Force
OPNAVINST	Naval Operations Instruction
USACE	U.S. Army Corps of Engineers
USN	U. S. Navy
UXO	Unexploded Ordnance

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MOBILE UNDERWATER DEBRIS SURVEY SYSTEM (MUDSS) FEASIBILITY DEMONSTRATION REPORT

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ABSTRACT

This paper reports on a feasibility demonstration executed by the MUDSS program. The purpose of the demonstration was to show the utility of a novel multi-sensor concept for the surveying of underwater ordnance and explosive waste.

INTRODUCTION

Purpose of the MUDSS Feasibility Demonstration

MUDSS is a three-year Strategic Environmental Research and Development Program technology demonstration project. Its purpose is to demonstrate technologies necessary to successfully survey underwater formerly used defense sites (FUDSs) for ordnance and explosive waste (OEW). The program is being executed jointly by the Coastal Systems Station (CSS) of the Naval Surface Warfare Center/ Dahlgren Division and by the Jet Propulsion Laboratory (JPL). MUDSS heavily leverages (1) acoustic, magnetic, and electro-optic (EO) minehunting sensor and signal and image processing technologies under development at CSS for the Office of Naval Research, (2) signal and image processing technologies and visualization technologies under development at JPL for the National Aeronautics and Space Administration, and (3) trace chemical detection technologies under development at JPL for the Federal Aviation Administration.

The MUDSS project is divided into two phases. Phase I, which ran through the first year of the project, culminated in an at-sea feasibility demonstration (FD) of a multi-sensor MUDSS prototype against OEW targets. The FD was successfully executed in August and September of 1995 in St. Andrew Bay (near Panama City, FL) and is the subject of this report. Phase II, which runs through the second and third years of the MUDSS project, will develop an advanced and refined MUDSS survey system from the experience with the MUDSS prototype in the FD. Phase II will culminate in a technology demonstration (TD) consisting of an OEW survey at a yet-to-be-determined FUDS.

The goal of the FD was to demonstrate first that the performance of a prototype MUDSS sensor suite consisting of on-hand acoustic, magnetic, and EO sensors similar to the proposed TD sensors shows good promise against OEW targets and is well characterized by sensor performance models already in place at CSS. The FD also had the goal of providing a multi-sensor data base to be used during Phase II to refine and develop signal and image processing algorithms, to develop the powerful sensor fusion capabilities necessary for successful underwater OEW surveying in difficult environments, and to develop visualization techniques and real-time survey control for the MUDSS TD. These FD goals were successfully met.

Description of the MUDSS FD System

A conceptual view of the MUDSS FD system is shown in Figure 1. The surface craft is a custom designed, magnetically and acoustically quiet, shallow draft, trailerable catamaran (see Figure 2). A dead-weight depressor (see Figure 3) suspended off of the back of the

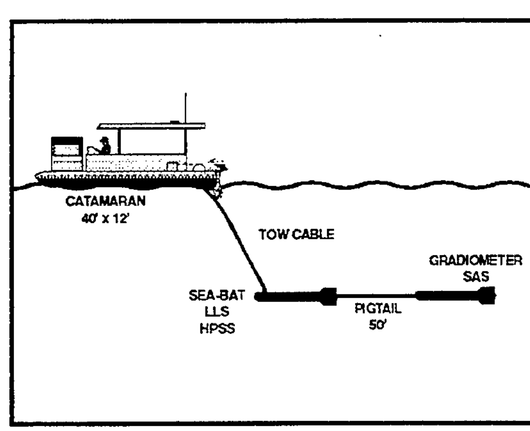

Figure 1. Sketch of the MUDSS FD system.

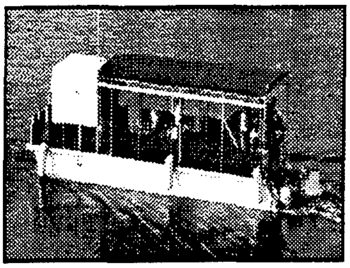

Figure 2. Photograph of the MUDSS FD catamaran. The white structure at the front of the catamaran is the instrument cabin. The dead-weight depressor can be seen at the back of the catamaran, where it is held by a capture device during transits to and from the test area.

catamaran houses a RESON Seabat ahead looking sonar, a CSS-developed high frequency sidescan sonar (the High Performance Sidescan Sonar, or HPSS; see Figure 4), and a laser linescanner (the LS 4096) leased from Raytheon Corporation. The laser linescanner is capable of 6mm resolution. The neutrally bouyant towed vehicle (see Figure 5) houses a CSS-developed low frequency synthetic aperture sonar known as the MADOM SAS and a CSS-developed superconducting magnetic field gradiometer (Figure 6). See Table 1 for a description of the three FD sonars.

The dead-weight depressor is suspended by the tow cable from a winch that controls the operating depth of the towed system. The cabin on board the catamaran, which together with the catamaran's 10 kW generator is placed near the front of the catamaran in order to maximize the distance from these two strongly magnetic objects to the gradiometer, provides space for an acoustics operator, a magnetics operator, an EO operator, the Global Positioning System (GPS) operator, and the sensor control and data acquisition systems.

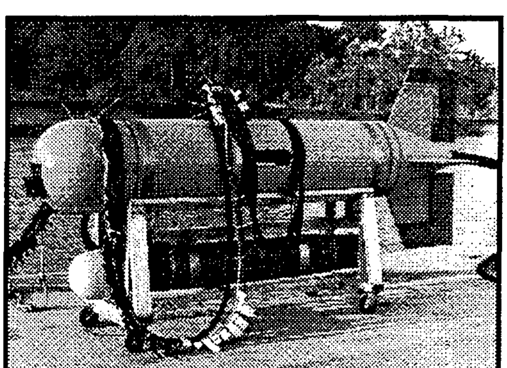

Figure 3. The MUDSS FD dead-weight depressor. The LS4096 is slung underneath the depressor, and the Seabat is visible protruding from the depressor nose. The HPSS looks out the starboard side of the depressor and is located opposite the access port visible in the middle of the depressor body.

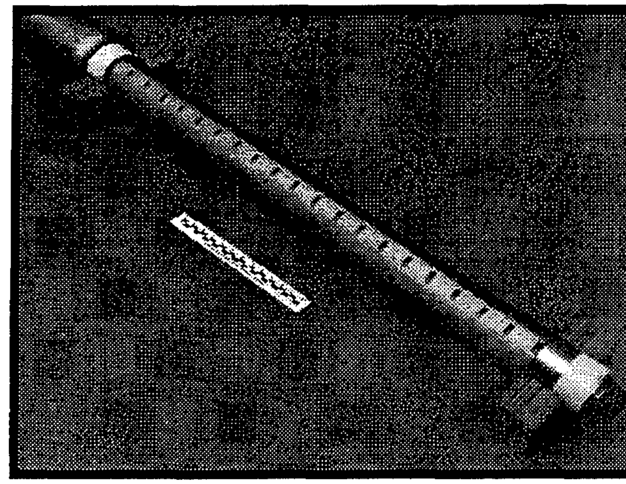

Figure 4. Photograph of the HPSS. The array is one meter long and contains ten 10-cm elements (because of limitations of the MUDSS FD sonar data link, only 5 of the 10 elements were used).

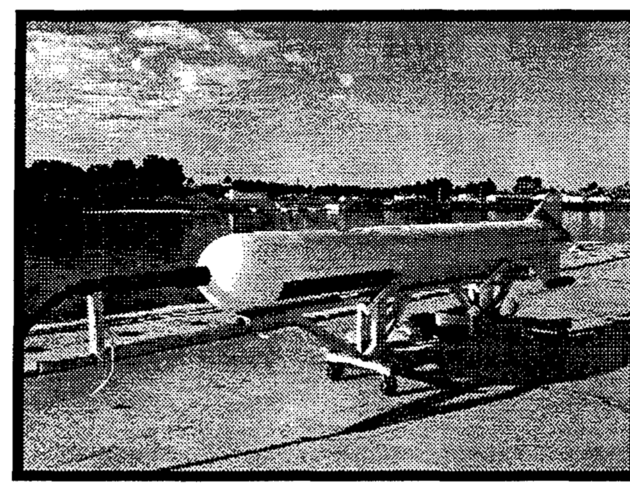

Figure 5. The MUDSS FD towed vehicle. This vehicle is towed from the end of the depressor by a 50-ft tether. It houses the MADOM SAS in the front of the vehicle and the superconducting gradiometer in an eight-foot long pressure vessel toward the back of the vehicle. The MADOM receive arrays consist of twelve three-inch elements (only the first four elements of the starboard side were used.

Description of the FD

The FD test area contained two target fields each having approximately a dozen OEW targets. The OEW targets in each of these fields spanned the full range of OEW target sizes, from 60 mm mortar shells to 2000 lb bombs. The targets are listed in Figure 7.

The first field, known as the clumped field, consisted of two concentric circles of targets with inner and outer radii

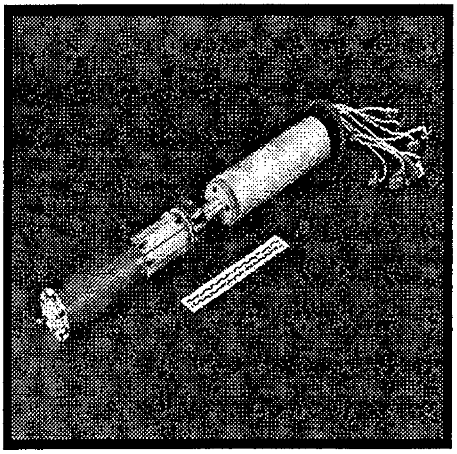

Figure 6. A picture of the probe of the superconducting gradiometer used in the MUDSS FD. The gradiometer pick-up loops are wound on the cylindrical substrate at far left, from which lines run to the Superconducting Quantum Interference Devices, which are located in shield cans seen at the center of the probe. The right-hand part of the probe is the neck plug. The whole probe slides into a dewar containing sufficient liquid helium to maintain the sensor at 4 Kelvins for two days.

of 10' and 35', respectively, each circle having six targets (see Figure 7). The purpose of the clumped field was to provide a high density of targets for efficient data collection by the acoustic and EO sensors. Because the gradiometer cannot distinguish targets that are closely spaced, another target field, called the linear field, was also laid out. The linear field consisted of a 663'-long row of small and medium-sized targets running north-south; a second, shorter row of three targets (two oil drums and a Mk82 bomb) parallel to, and 30' east of, the first row; and a third parallel row of two targets (Mk83 and Mk84 bombs) 30' east of the second row (see Figure 7). For ease of interpretation of the sonar images, which depend strongly on target aspect, the targets in both fields were placed so that the axis of symmetry of each target pointed north.

Table 1. Characteristics of the MUDSS FD sonars

	Side Scan Sonar		Ahead Looking Sonar
Sonar	MADOM SAS	HFSS	RESON Seabat 6012
Sensor Type	Synthetic Aperture Side Looker	Synthetic Aperture Side Looker	Ahead Looker
Center Frequency	16.5 kHz	600 kHz	455 kHz
Azimuth Resolution	7.5 cm	5 cm	1.5°
Range Resolution	7.5 cm	20 cm	5 cm
Maximum Speed	5 Knots	5 Knots	7 Knots
Range @ 5 Knots	0.6 - 35 m	4 - 35 m	5 - 200 m
Receiver Array Length	30 cm	40 cm	
Number of Beams	1	1	60 (90° sector)
Hydrophone Horizontal Beamwidth	69.4°	1.4°	
Hydrophone Length	7.5 cm	10 cm	
Number of Staves	4	4	
Hydrophone Vertical Beamwidth	45°	13°	15°
Projector Horizontal Beamwidth	34.8°	1.4°	165°
Projector Length	15 cm	10 cm	
Projector Vertical Beamwidth	45°	13°	15°
Depression Angle	5°	10°	15°
Bandwidth	10 kHz	4 kHz	
Sampling Frequency	64.789 kHz	64.789 kHz	

Over 150 runs were made against these target fields with various combinations of sensors functioning, including over 30 runs with all sensors functioning simultaneously. The FD sensors did well against these targets, performing close to the predictions of CSS's acoustic, magnetic, and EO models.

The relatively small portions of the HPSS and MADOM SAS data containing targets of interest were beamformed and motion compensated off line to produce digital images. These images were archived for each run on 4mm digital data tape along with the corresponding LS4096 digital images, the raw gradiometer digital data (including magnetometer channel data for motion compensation purposes), and the digital GPS data. This data, together with copies of the Seabat video data, are being used to develop automated processing, sensor fusion, and visualization capabilities for MUDSS.

In addition to the sensor and GPS data, environmental data was also taken during the FD. This data was

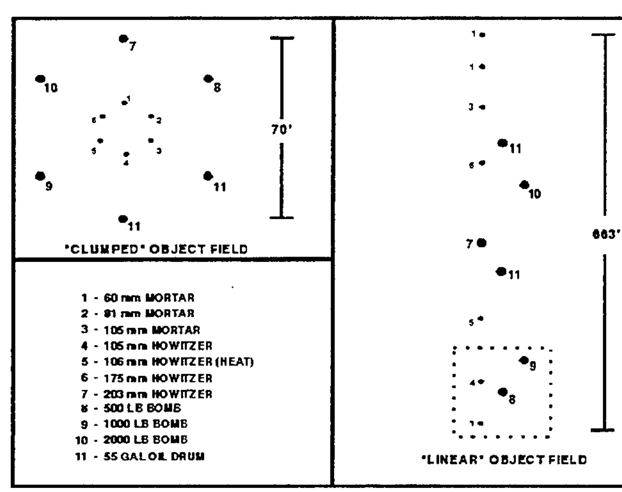

Figure 7. A list of the FD targets and diagrams of the two FD target fields.

collected from a small boat anchored a few hundred feet from the clumped field, and included sound velocity profile and optical attenuation and scattering profiles at 532 nm (the operating wavelength of the LS4096). The environmental data, which was collected roughly at hourly intervals during the FD, is described in a separate report (Larson [1996]).

ACOUSTICS RESULTS

Introduction

The purpose of the acoustics analysis of the FD is to show that the sonar performance prediction model known as SWAT (Shallow Water Acoustics Toolset), which was developed at CSS to predict the performance against sea mines of imaging sonars operating in the difficult shallow water environment, is able to explain the performance of the FD sonars against the FD target fields. The validation of SWAT for the FD sonar data then enables the MUDSS project to proceed with confidence to performance predictions for the TD and to future sonar design tradeoffs for the MUDSS systems that will follow the TD.

The two main measures of effectiveness of SWAT for the FD are the fidelity of the predicted target images and the fidelity of the predicted intensities of the general background returns (known as "reverberation") and signal-to-noise ratios (SNRs). For illustrative purposes,in this report we present reverberation/SNR and target image analyses for a single selected run (Run 44) over the clumped field. Run 44 was chosen because the closest point of approach to the center of the clumped field during this run put the entire field within the range of the HPSS and MADOM SAS, and because the targets are presented at a representative aspect (roughly 45 degrees).

Image Analysis

The MADOM SAS, HPSS, and Seabat images from Run 44, which even with no accompanying analysis provide an excellent qualitative summary of the relative merits and capabilities of the three FD sonars, are shown in Figures 8 and 9. Excellent target size and shape information is evident in these figures. (In the MADOM SAS and HPSS images shown in these figures, the sonar motion was from right to left at the bottom of the figures. The nearest

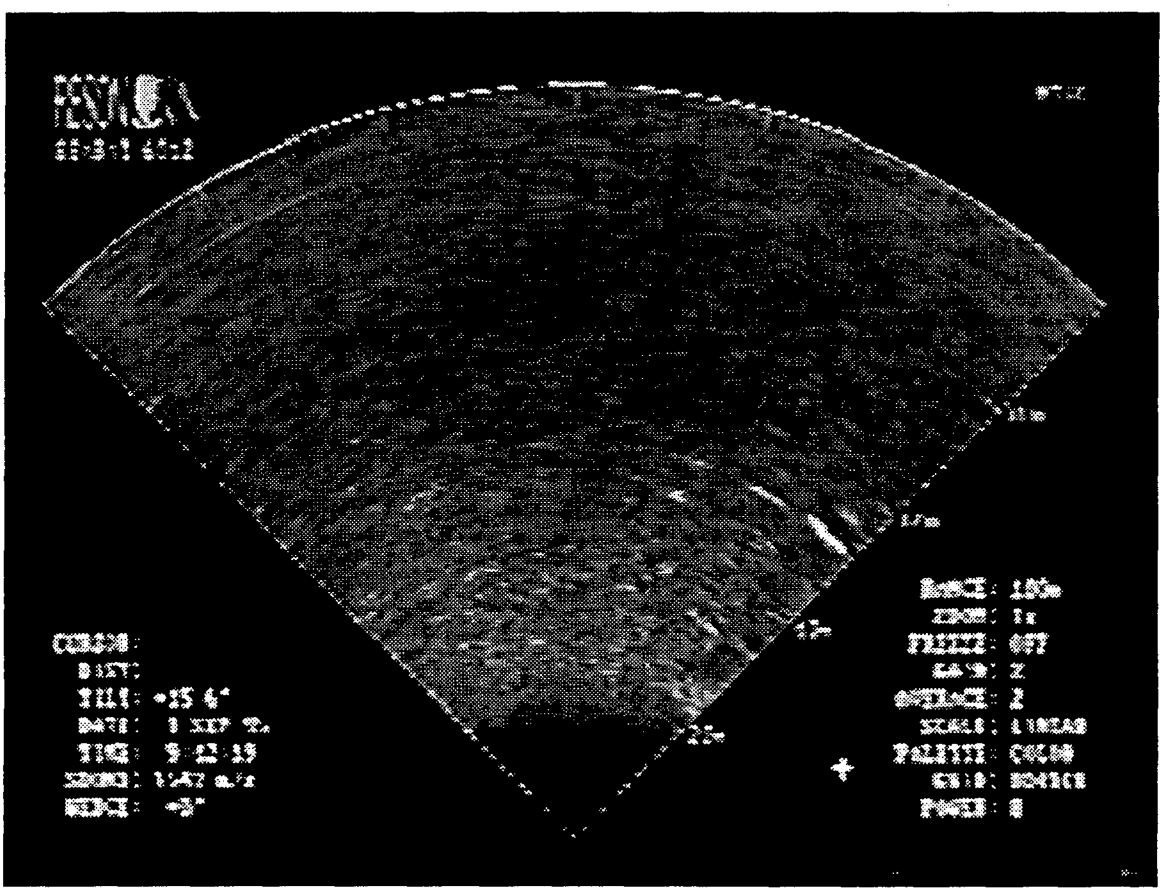

Figure 8. The Seabat image of the clumped field for Run 44. The clumped field appears to starboard at a range of between 30m and 50m. The larger targets in the outer ring can be discerned above the general clutter (multipathing obscures the clutter at ranges greater than about 50 m), with the 1000-lb and 2000-lb bomb images showing up prominently. The targets in the inner ring are not discernible above the general clutter.

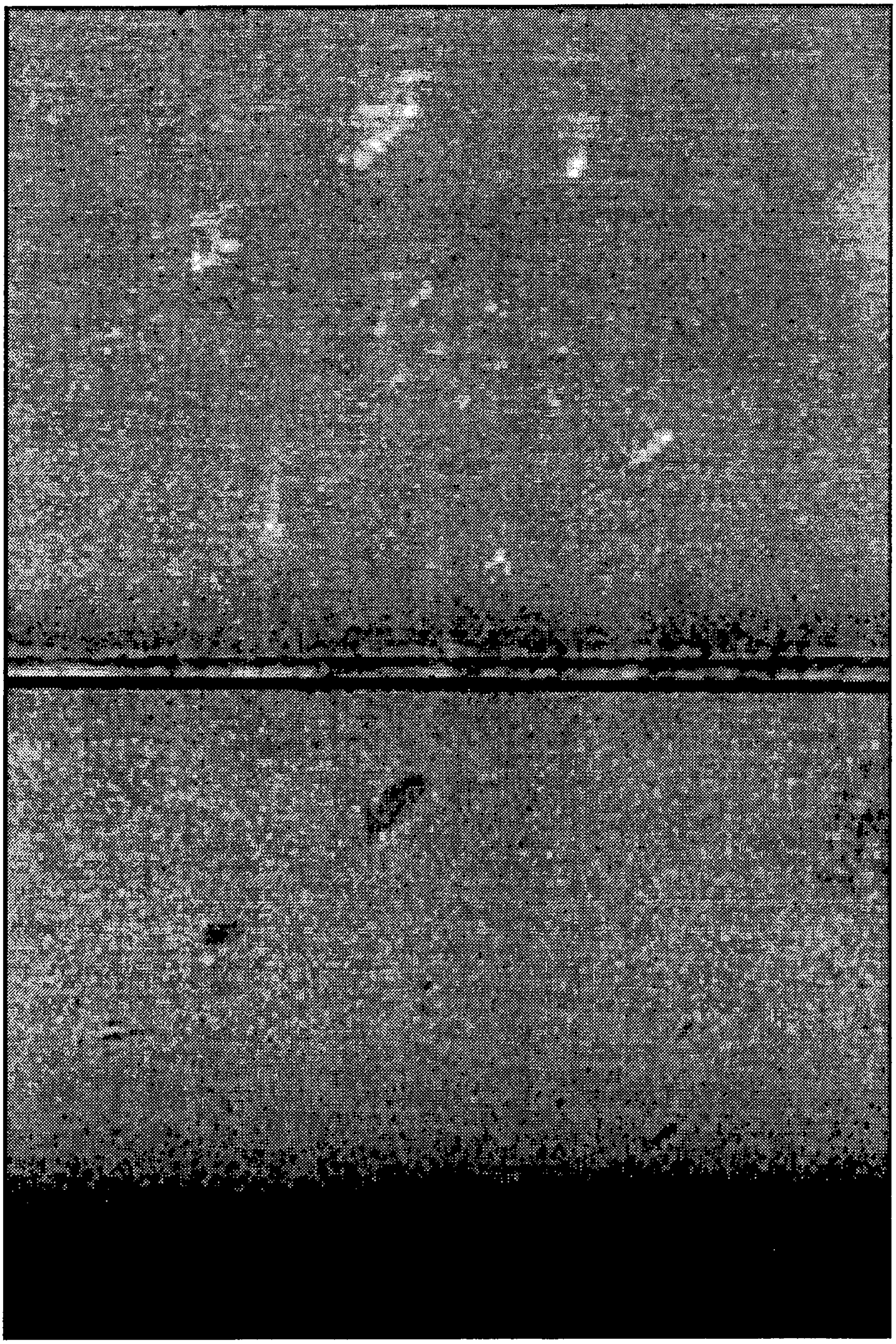

Figure 9 (Top). The MADOM SAS image of the clumped field for Run 44, showing outstanding target size and shape information. The object visible in the center of the small ring of six targets is a screw anchor used by divers in positioning the targets. "Ghost" images from the first multi-path (sonar to target to water surface to sonar) can be seen for the brighter targets at the longer ranges. Figure 9 (Bottom). The HPSS image of the clumped field for Run 44. Because of the HPSS's narrow vertical beam (13 degrees) and small depression angle (10 degrees), the first returns from the bottom come at a range of 12 to 13 meters. The direct returns from the targets are relatively weak because of the high operating frequency (600 kHz) of the HPSS, but the shadows provide good shape information for a few of the targets.

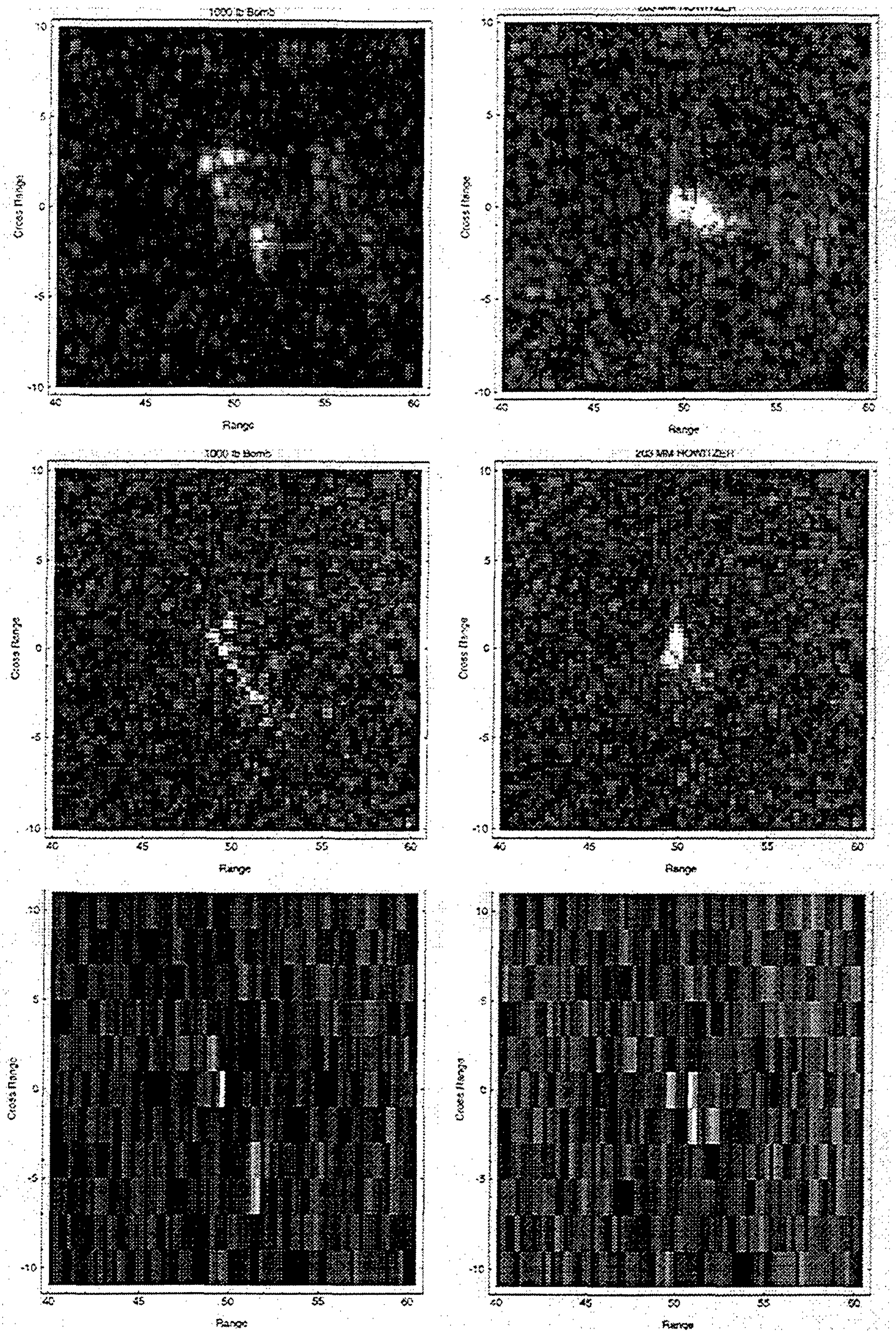

Figure 10. Images of a 1000 lb bomb (left column) and 203 mm howitzer (right column) as actually seen by the MADOM SAS in Run 44 (first row), as predicted by SWAT for the MADOM SAS under the conditions of Run 44 (second row), and as predicted by SWAT for a high-quality 100 kHz commercial sidescan sonar under the conditions of Run 44 (third row). Dimensions are in feet.

recorded range was 2.0 m, the farthest range was 35 m, and the operating height was between 3.0 m and 4.5 m.)

A comparison among actual MADOM SAS images of the 1000 lb bomb and 203 mm howitzer shell from Run 44, the corresponding images simulated by SWAT for the MADOM SAS, and the corresponding images simulated by SWAT for a high-quality 100 kHz commercial sidescan sonar are shown in Figure 10. Figure 10 illustrates the application of SWAT both as a performance analysis tool and as a performance prediction tool.

Reverberation/SNR Analysis

It is evident that the performance of the MADOM SAS against these targets was clearly far superior to the performance of the HPSS and the Seabat, with the exception of the shadowing, which is almost non-existent in the MADOM SAS images and strong in the HPSS and Seabat images. The correct modeling of these performance features requires correct modeling of target strengths and of reverberation (including multi-pathing).

Figures 11 and 12 illustrate the fidelity of SWAT in modeling target strengths and reverberation, respectively.

Figure 13 shows the aspect-averaged SNRs predicted by SWAT for the three FD sonars against a 203 mm howitzer shell for the environmental conditions of Run 44. The predicted superiority of the MADOM SAS is evident in this figure.

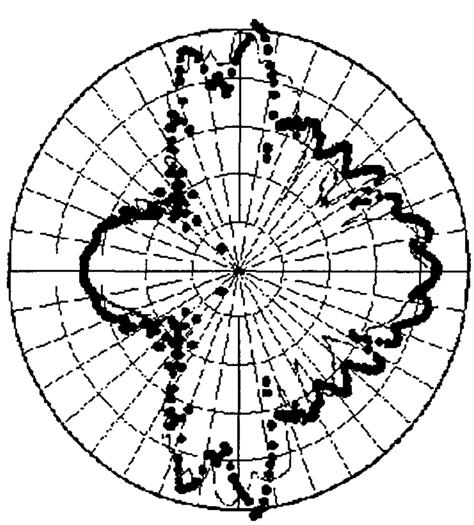

Figure 11. Target strength measurements and SWAT predictions for a 203 mm howitzer shell at 20 kHz.

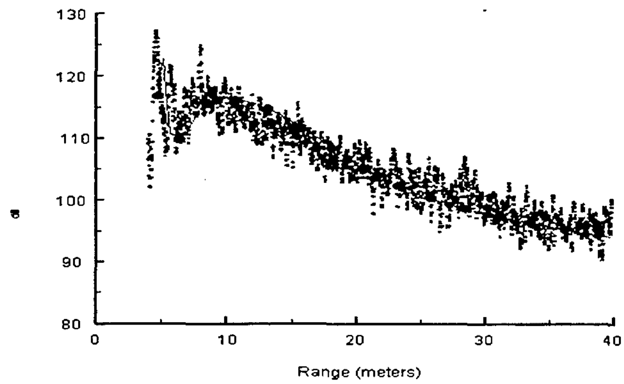

Figure 12. Predicted (circles) versus measured (dots) total reverberation for the MADOM SAS in Run 44.

HPSS images are of course superior to the Seabat images because of the HPSS's higher azimuthal resolution. The shadowing seen with these two sonars is comparable in depth, essentially because their operating frequencies, vertical beamwidths, and depression angles are comparable. The shadow depth is deeper for the HPSS and Seabat than for the MADOM SAS because their vertical beams are narrower (thus reducing multi-pathing) and because reverberation off the sea surface is a decreasing function of frequency. SWAT predictions for the shadow depths in Run 44 for these three sonars are shown in Figure 14.

ELECTRO-OPTICS RESULTS

Introduction

The goal of the electro-optics analysis is to show that the target images produced by the LS4096 during the FD can be accurately simulated by IMPERSonator (Imaging PERformance Simulation), the CSS simulator for underwater imaging systems. IMPERSonator simulates the propagation of light through the transmission optics (if

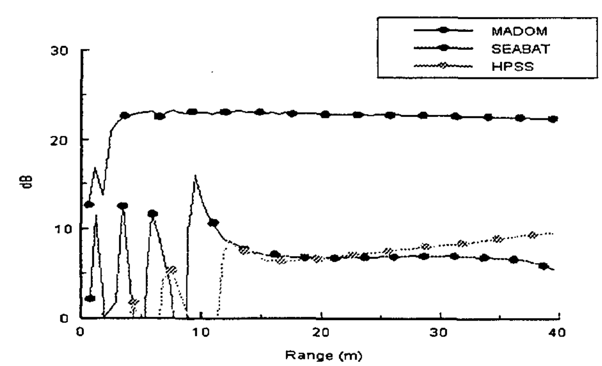

Figure 13. SWAT predictions for the aspect-averaged SNR for the Seabat, MADOM SAS, and HPSS against a 203 mm howitzer shell for the environmental conditions of Run 44.

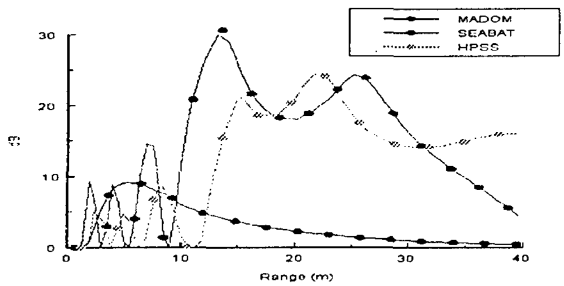

Figure 14. SWAT predictions for the shadow depth of the Seabat, MADOM SAS, and HPSS under the conditions of Run 44.

any) of the underwater imaging system, the absorption and scattering (forward and backward) of light (including ambient light as well as any active source light) as it travels through the water toward the target, the scattering of light from the target (which is modeled as a Lambertian scatterer), the absorption and scattering of light traveling to the receiver, the propagation of light through the receiver optics, and the conversion of the received light to electrical signals.

The medium propagation modeling portions of IMPERSonator in principle require in-situ profiles at the system wavelength (532 nm in the case of the LS4096) of ambient light, the absorption coefficient, and the differential scattering cross section. The target scattering modeling requires digital target images for target shape and for wetted reflectivity measurements.

In practice, measurements were made at the FD test site of ambient light at the surface and of profiles of the absorption coefficient and small-angle forward scattering. These measurements were made continuously during the execution of the FD (see Larson [1996]). The differential scattering cross section was modeled from the measured absorption and small-angle forward scattering profiles by assuming a standard "Maalox" scattering for the medium.

With these profiles, typical attenuation lengths during the FD were around 1.5 m. Since the field of view of the LS4096 is 70 degrees (centered on nadir) and the operating height was generally between 4 m and 5 m, the ranges to the targets during the FD were generally between 4 m and 6 m (roughly 2.5 to 4 attenuation lengths).

Analysis of LS4096 Images

Examples of LS4096 images for the smallest and largest of the FD targets are shown in Figures 15 and 16. Because a laser linescanner casts no shadows, the targets often appear peculiarly flattened, especially if the scattering from them is accurately Lambertian (see Figure 16).

Figure 17 (see page 9) shows a comparison between actual LS4096 target images and images simulated by IMPERSonator (for the experimental operating conditions under which the actual images were taken) for the LS4096 and for a simple passive camera. Notice the flattened appearance of the simulated targets. The simulated images for the passive camera were obtained using ambient light for illumination, and so represent the performance of a simple camera at its best (nighttime operation would require artificial illumination, backscatter from which typically grossly limits the maximum useful range of a simple camera).

Figure 15. LS4096 image of a 60 mm mortar at a range of 5m (3.5m attenuation lengths).

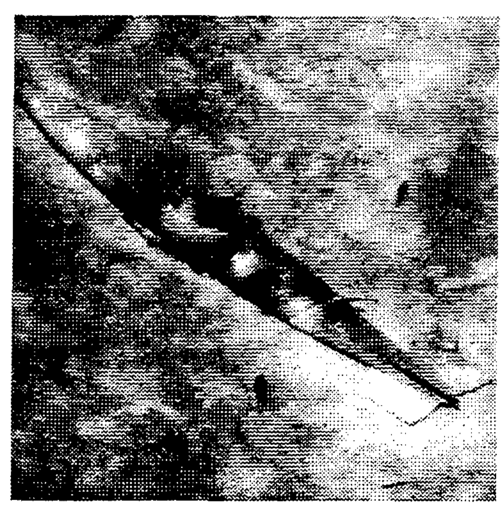

Figure 16. LS4096 image of a 2000 lb bomb at a range of 4 m (3 attenuation lengths).

GRADIOMETER ANALYSIS

Introduction

The FD used a superconducting magnetic field gradiometer developed at CSS for hunting sea mines. This gradiometer has two principal advantages over simpler, more common magnetic field sensors such as total field magnetometers: first, it has the highest known sensitivity of any field-deployable magnetic sensor, providing it with excellent range (over 50 m against a 2000 lb bomb); secondly, its five channels measure all of the independent components of the gradient of the magnetic field, providing sufficient information to localize simultaneously on as many as three magnetic targets. By comparison, a total field magnetometer has only one channel and cannot unambiguously localize on even a single target.

In addition to being able to find the positions of multiple magnetic targets, the gradiometer also determines their magnetic moments. This magnetic classification information can then be used in conjunction with the sonar images to help correctly classify OEW targets and sort them out from the surrounding debris.

Localization and Moment Classification

A portion of the gradiometer time series from a pass near the 1000 lb bomb in the linear field is shown in Figure 18. An automatic localization algorithm operates on signals such as these to determine the locations and magnetic moments of the targets contributing to the signals. In Figure 18, this algorithm finds a target having the magnetic moment of a 1000 lb bomb located 15 m to port and 5 m below the gradiometer, very close to the known location of the actual bomb.Figure 19 shows the locations of the magnetic targets found by the gradiometer in a pass over the linear field (the gradiometer trajectory as inferred from the GPS data can be seen in the figure). The size of the dot at each target location is in proportion to the size of the magnetic moment found for the target, illustrating the capability of the gradiometer to distinguish between large and small targets.

It is evident from Figure 19 that all of the targets in the linear field, whose actual positions are marked with open circles, have been found by the gradiometer with the exception of the 1000 lb bomb. The localization algorithm instead found a second target at the location of the 500 lb bomb and another (false) target further on to port. Errors of this sort can arise when targets are too closely spaced.

CONCLUSION

The FD succeeded in its objectives of (1) showing that on-hand Navy sensors have a good classification and identification capability against OEW targets; (2)

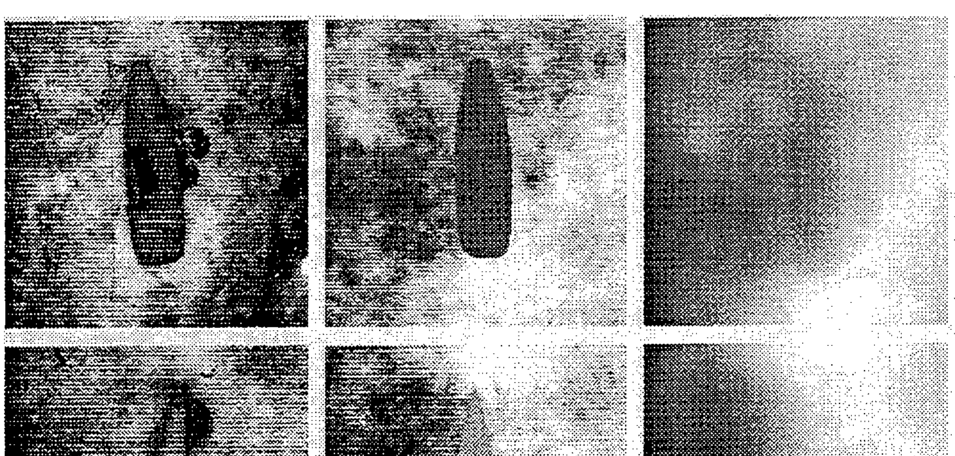

Figure 17. Comparison between actual LS4096 images (first column) and IMPERSonator predictions for the LS4096 (second column) and for a simple passive camera (third column). The targets are a 203 mm howitzer shell (first row) and a 155 mm howitzer shell (second row).

demonstrating that CSS simulations of acoustic, electro-optic, and magnetic sensor performance accurately account for the performance of these sensors in the FD; and (3) establishing a useful data base for the development of acoustic and electro-optic aided target recognition algorithms.

ACKNOWLEDGEMENTS

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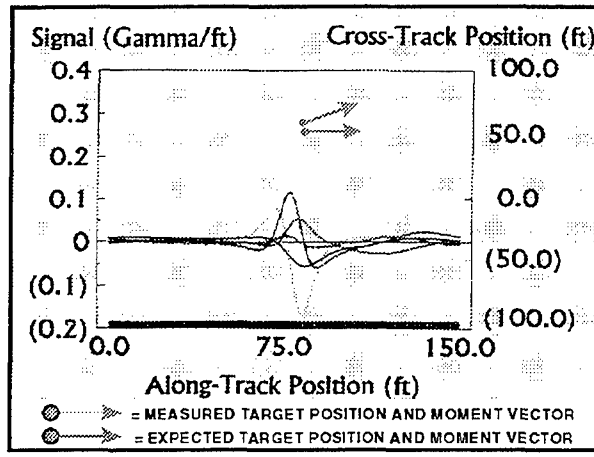

Figure 18. The five gradiometer signals in a 150-ft section of data on a pass near the 1000 lb bomb in the linear target field. The signals are due principally to the bomb, although other targets in the field are contributing, as is evident in the tails of the signals. The measured and expected target location and moment are also displayed. The expected direction of the moment vector is determined from knowledge of the orientation and shape of the target, whose moment is mainly induced.

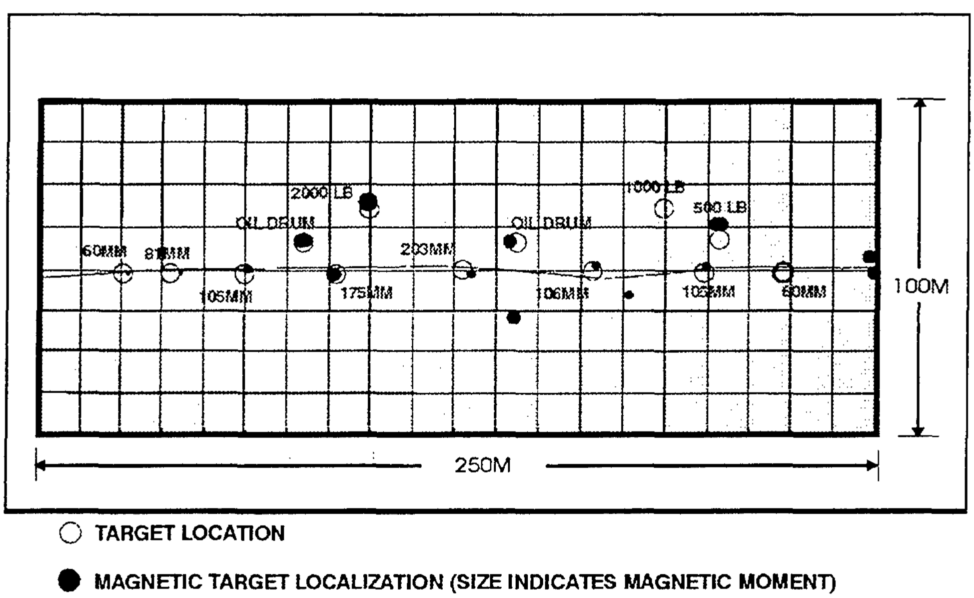

Figure 19. Gradiometer targets (black circles) found in Run 118 over the linear field. The size of each black circle is proportional to the size of the target moment. The open circles are the actual target locations. The gradiometer trajectory as inferred from the GPS measurements can be seen in the middle of the figure.

Underwater Ultrasonic Imaging for Target Threat Assessment

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INTRODUCTION

One of the major obstacles to restoration of U.S. Department of Defense (DOD) sites is unexploded ordnance (UXO) contamination. In many cases, nearby lakes, rivers, and coastal waters have been contaminated with both ground and underwater UXO. One such example is the island of Kahoolawe, part of the Hawaiian Islands, which served as a bombing range for the U.S. Navy in the Pacific. Rockets, mortars, anti-personnel bombs, and submunitions targeted for the island wound up in coastal waters as well. It has been estimated that ten percent of the ordnance did not explode at the time as designed but still could. [Murphy, 1996]

Technologies need to be developed to allow missions where underwater UXO is detected, tagged with a location, and finally remediated. The underwater UXO mission is similar to a mine countermeasures mission (MCM) in some respects. In a typical MCM mission, a large area search system detects suspected targets and tags them with a GPS position. Due to the man-made clutter and natural geographic features in the survey area, some marked objects will be actual threats and others will not be. The GPS coordinates of the suspected threats are passed to an explosive ordnance disposal (EOD) team. The EOD team, in a rubber raft, uses a portable GPS unit to reacquire the suspect anomaly position. Standard EOD tactics are then used to verify the object as an actual mine threat or non-threat. Then, EOD procedures are employed to neutralize or render safe the mine. One of the major problems for the EOD diver is verification of the threat. Rivers, harbors and very shallow water coastlines typically have poor visibility. Very often the diver must physically touch the object to classify it as a mine or non-threat.

The Naval EOD Technology Division (NAVEODTECHDIV) has been working in underwater acoustic imaging technologies for the past five years. One of the goals of the program is to develop technologies which will lead to the development of a diver-held imaging sonar capable of identifying the target orientation and target features as small as 1 cm^3. Underwater UXO divers will have to investigate previously marked targets as UXO or false targets and could potentially use high resolution sonar technology to do so.

This paper will present results of high resolution acoustic experiments performed [Johnson, 1993, 1995] and identify some of the current technology issues being addressed. The author would like to thank Don Folds of Arinc Research Corp., Ed Belcher of the Applied Physics Lab, University of Washington, and Behzad Kamgar-Parsi of the Naval Research Lab for their contributions to this work.

SINGLE BEAM EXPERIMENTS

The underwater imaging experiments were performed in an anechoic test tank at the NAVEODTECHDIV where the target was placed at a distance of 1.9 meters. Both line focus and point focus configurations were evaluated for classification effectiveness. The first configuration is a line focus system generating a fan beam; narrow in one direction and wide in the other as shown in figure 1. The

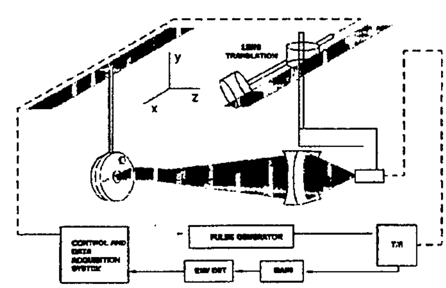

Figure 1 Line Focus Experimental Configuration

beam is formed by a line element placed at the on-axis focal point of an acoustic lens. The -3 dB beamwidth is 0.17 degrees by 3 degrees with the first sidelobe at least 45 dB down. After the first target set, an improved transducer was delivered. In conjunction with the cylindrical lens, the new transducer element formed a 0.15 degree by 15 degree beam. The larger field of view improves the target coverage. The single fan beam is raster scanned across the target to form the image.

The second test configuration is a point focus system where the beam created can be visualized as an expanding cone. A spherical acoustic lens with a button element placed at the on-axis focal point in conjunction with topside electronics is used to create the beam as shown in Figure 2. The system -3 dB beamwidth is .16 degrees with the first sidelobe at least 45 dB down. This single beam was then raster scanned down and across the test target to fully form an image. Since only one beam is created at a time, there is no electrical or acoustic crosstalk. Therefore, the images created are best case.

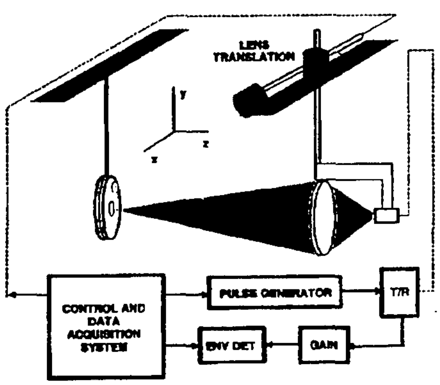

Figure 2 Point Focus Experimental Configuration

Suspended Targets

In mine clearance efforts, moored targets are of significant interest and are easier to image due to the lack of bottom interactions. Therefore, a suspended target in the water column was chosen for the first experiment. One target image generated is of the mine-like plate with different circular sub features and raised fins shown in Figure 3. Figures 4 and 5 allow for comparison of line focus and point focus imaging technologies. These are post-processed images formed by application of 3D volume rendering techniques, high frequency emphasis filtering, and smoothing algorithms as appropriate. [Kamgar-Parsi, 1995] Three different grazing angles are shown for the fan beam case. The grazing angle is the angle formed by a ray representing the beam and the plane parallel to the target. The smaller the grazing angle,

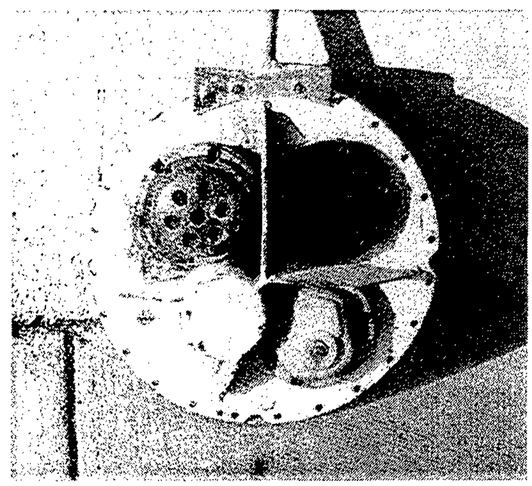

Figure 3 Mine-like Plate

the more elongated the target appears since returns come from a greater range of distances. In all of the line focus images, the circular plate and target holder are visible as well as a bright specular return where one of the fins meets the plate. The circular sub features and fins are visible to various degrees at each angle. However, it is difficult to classify the sub features at any one angle without prior knowledge of the target. The different grazing angles do enhance the ability to differentiate the sub features. The two sub features that are easily perceptible are the ones on the left hand side of the images. At the 30° grazing angle the feature with holes is identifiable and the tall cylinder below is visible at all of the grazing angles. At the 60° grazing angle, the sub-features on the right hand side of the photograph appear to be visible and distinguishable from each other. By using several aspect angles, all of the sub features are identifiable to a limited degree. The conical beam image, by comparison, allows for accurate classification of the four sub features and fins with the single 90 degree grazing angle.

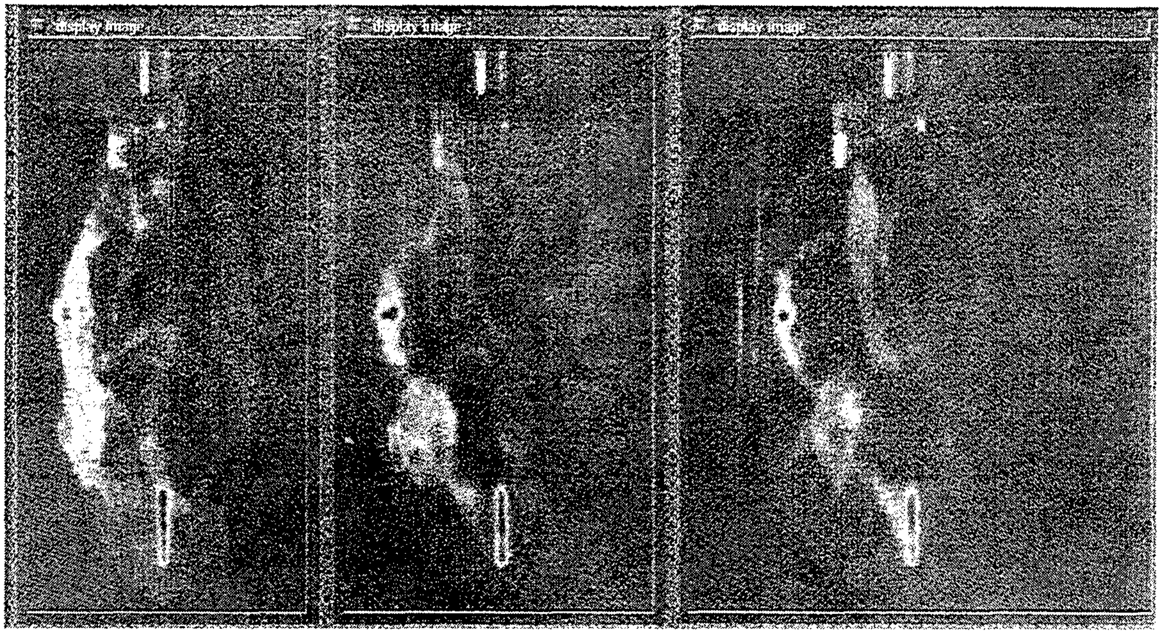

Figure 4 Line Focus Images of Suspended Mine-like Plate at 60, 45, and 30 Degree Grazing Angles

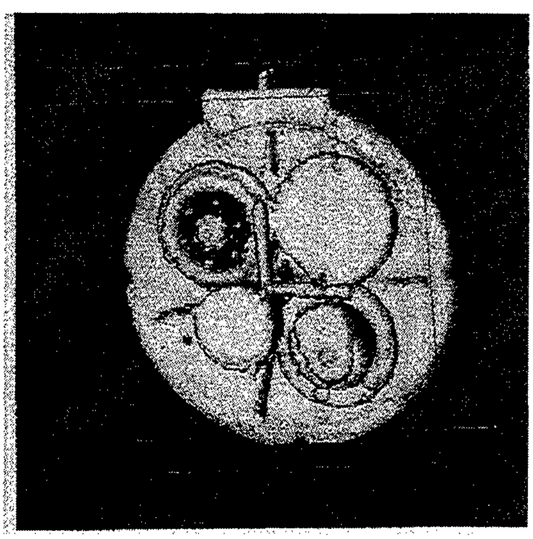

Figure 5 Point Focus Image of Suspended Mine-like Plate

Bottom Targets

The suspended target point focus images are good enough to provide classification capability. The line focus images provide a limited classification capability. Bottom targets present a greater imaging challenge due to interference from acoustic energy reflected from the bottom. Another set of experiments was conducted to image bottom targets which is of more interest for UXO identification. Instead of placing targets suspended on a pole, targets were placed in a 3 foot wide by 4 foot long by 1 inch deep pan filled with sand and pebbles of the size typically found at the beach. The lens assembly was tilted down to a depression angle of 24 degrees to ensonify the bottom and target. Results of the line focus experiments are presented first.

A fan beam image of target 1, the mine-like plate previously described, is shown in figure 6. The image is an overhead view of the returns on each ping line. The closest returns appear on the left and the farther returns on the right of the image. The pan containing the sand is visible as a green colored rectangle. None of the circular sub features or fins are visible. Some bright returns from

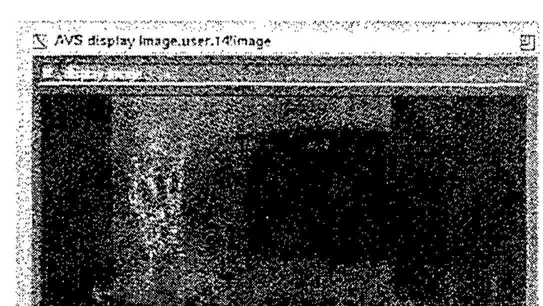

Figure 6 Line Focus Image of Mine-Like Plate on Bottom

the front face plate are visible, but the level of detail is insufficient to identify any of the target characteristics.

Target 2 is a 45 cm diameter cylinder section with a recessed well as shown in Figure 7. The recessed well is a flat plate with eight symmetric bolt ends with nuts attached. There is an additional bolt end wthout a nut on it for a total of nine objects on the well surface. The nuts are .75 inches wide. The cylinder was placed on the bottom with the normal to the recessed well parallel to the bottom facing the lens assembly.

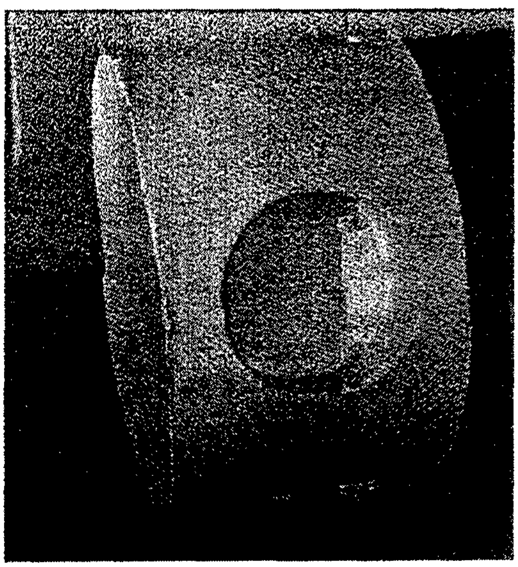

Figure 7 Cylinder Section with Recessed Well

The image shown in Figure 8 is an overhead view of the returns on each ping line. The pan containing the sand is discernible but the cylinder shows up only as series of lines of varying brightness in the shadow region of the target. Moving from left to right, the first line is the return from that portion of the cylinder normal to the beam. The area of clutter and second line directly behind this first one are due mainly to bottom returns below the cylinder and where the cylinder meets the sand bottom. Based on the time of arrival, the next line occurs at a distance equal to the radius of the cylinder. The next line, a wider less bright one, occurs at the one diameter distance, a reflection off the back wall of the air filled cylinder. The last line occurs at the two diameter distance representing a multiple reflection inside the cylinder. Several other minor lines are visible as well and are due to a combination of internal reflections and possibly creeping waves navigating the cylinder circumference.

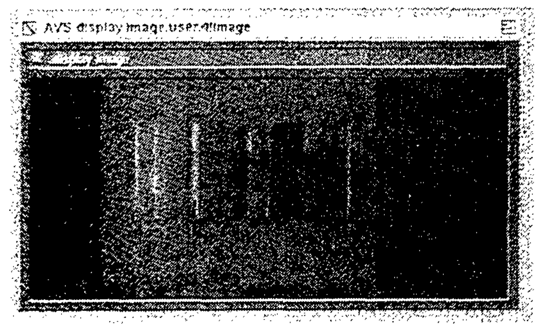

Figure 8 Line Focus Image of Cylinder with Recessed Well on the Bottom

Target 3 is the front section from the same 45 cm diameter cylinder and is shown in Figure 9. The front end has a symmetrical eight-nut/bolt arrangement surrounded by a circular groove. There is another slightly raised cylinder next to it and then a 26° sloping surface. The target was placed with the face containing the bolt heads perpendicular to the bottom and normal to the end of the tank where the lens assembly was located.

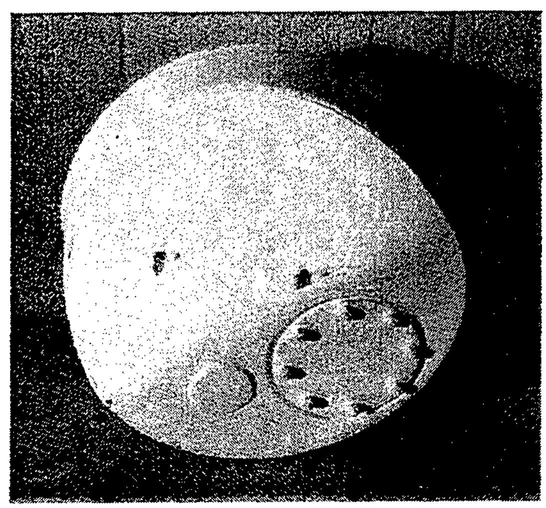

Figure 9 Sloped Front End of Cylinder

The face with no features was therefore oblique to the incoming beam. The image representation is the same as the previous. The pan containing the sand and a large shadow are easily visible. There are no identifiable target features. The degree of slope on the front face appears exaggerated in the image and the shadow is strangely shaped. Little correlation exists between the target and the image generated as shown in figure 10.

Figure 10 Line Focus Image of Sloped Front End of Cylinderon Bottom

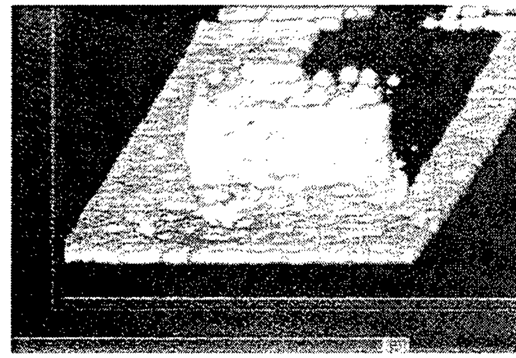

Figure 12 Point Focus Image of Cylinder with Bolt Pattern and Fin on Bottom

The last bottom target is Target 4, a cylinder with two bolt patterns on it and a fin as shown in Figure 11. The image in Figure 12 was created using the laboratory point focus system. The bolts are .25" in diameter and the raised fin is 1.75" tall. The target was oriented such that the cylinder rested on the bottom with its fin perpendicularly aligned with the bottom and the cylinder axis parallel to the tank end where the lens assembly was placed. The image is a 3D volume rendered image produced by the Naval Research Laboratory (NRL). Both bolt patterns and the fin are visible . The shadow is well defined and the cylindrical nature of the object is revealed.

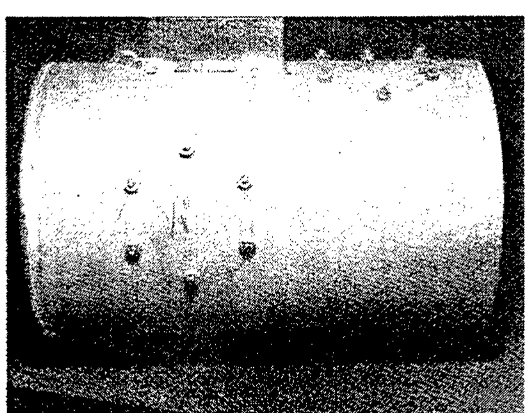

Figure 11 Cylinder with bolt pattern and fin

POINT FOCUS IMAGING TECHNOLOGY

The results of these experiments indicate that for classification of fuzing mechanisms, bolt patterns, and other mine features, point focus systems have to be employed especially if bottom targets are expected. The technology to develop a compact point focus imager with thousands of beams, electrical interconnects, and sufficient signal processing capability needs to be developed to realize the level of classification required. Two approaches are discussed below.

Mill's Cross Array and the Acoustic Imaging System

One approach to a achieving a point focus system without having to generate thousands of beams simultaneously is a Mills Cross array configuration. The basic approach is shown in figure 13. Two line focus systems generating orthogonal fan beams are employed. One system is in receive mode. The other transmits forming a beam at the top of the receiver's vertical field of view. After the data is received, the transmitting array forms another beam -3 dB below the previous. This continues until the entire image frame is generated. The obvious disadvantage is that image acquisition is accomplished over a series of transmit/receive cycles. Incorporating a multi-frequency design can reduce the image acquisition time by a factor of the number of frequencies used, but would require a complex receiver design utilizing filters to separate the signals.

As an intermediate step, a laboratory acoustic imaging system (AIS) was developed to look at the effects of inter-element crosstalk, sidelobe level and multi-lens designs on image quality. Eventually this system will be improved to operate in a Mill's Cross configuration. The AIS as currently configured is a fan beam system operating at 3 MHz. The beams are .25 degrees by 11 degrees with the first sidelobe -15 dB down. The 96 beams are created by a 48 element transducer in the focal plane of a 2 lens focussing system. [Belcher, 1995] Two lenses are required because of the desire for a flat array in the focal plane. A single lens system would require a curved hemispherical array for optimum focus. The flat

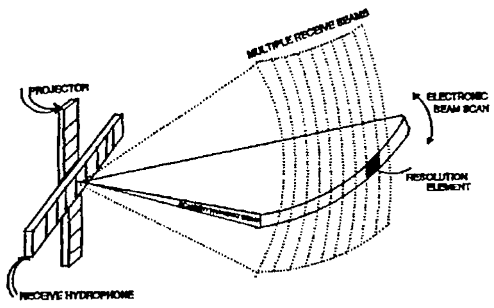

Figure 13 Mill's Cross Array Configuration

array is desirable since it can be more easily manufactured. The array transmits and receives on all channels and then is shifted by the -3 dB spacing repeating the transmit/receive cycle to form an entire image in one second. An image of the mine-like plate is shown in Figure 14. The image does not convey as much information as the single beam system image generated by raster scanning across the target. One reason is the useable dynamic range of the AIS system is on the order of 20 dB instead of the 40 dB available in the previous experiment. Areas of the target appear black where signal return is below the useable dynamic range of the system.

Figure 14 Advanced Imaging System Image of a Suspended Mine-like Plate

Another reason for the poorer image is the AIS sidelobe levels are much higher at approximately -20 dB down than in the earlier experiments. The large specular reflectors on the target result in acoustic scattering entering the sidelobes and blurring the image. In the image this is seen as a large return at the same range on all of the beams. The single beam experiments used an oversized element and aperture to achieve the lower sidelobes. The larger array size and more complex lens design required for a system with multiple oversized elements precludes these options for sidelobe reduction. An aperture shading technology is being researched to reduce sidelobe levels.

A third reason for the poorer image quality, which will become even more important in a higher dynamic range system, is reverberation inside the multi-lens beamformer. Energy bounces between the lenses and slit, then enters the element at later times with reduced levels. In the image, this is most noticeable as two lower return level lines behind the specular reflector caused lines. A highly absorptive material has been purchased and found to reduce the reverberation when used to cover the slit mechanism. Covering the inside of the baffle too should eliminate the image ghosting.

Current work with the AIS is focussing on modifying the software and adding a second orthogonal array as a transmitter to process the collected data in a Mill's Cross configuration. In order to demonstrate the full capability of a Mill's Cross configuration, as mentioned above, improvements in the dynamic range, sidelobe levels, and reverberation are taking place.

Fully Populated Array

The alternative to the Mill's Cross under consideration as part of the current program is a fully populated array in the focal plane of a spherical lens, one element for every beam. A .25 degree beam system with a 25 degree field of view would then require a 100 x 100 array. This is 10,000 elements even for a small field of view!

Based on the experimental imaging results, laboratory analysis of the acoustic lens beamformer performance, and array and electronics modeling, the following array and receiver target specifications have been generated as a baseline:

Array Size	100x100
Element Size	1 mm^2 or 1mm diameter
Element Spacing	1.75 mm center to center

Transmit Voltage Response	150 dB re 1uPa/v @ 1m
Free Field Voltage Sensitivity	-215 dB re 1v/uPa
Transmit Voltage	100 volts peak to peak
Crosstalk	<50 dB
Update rate	4/second minimum
Dynamic Range	>70 dB
Minimum Signal	1.6 uV rms
Bandwidth	75 KHz
Operating Depth	300 feet

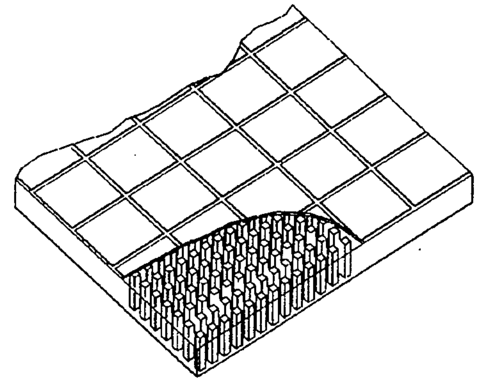

Figure 15 A Composite Array with Sub-diced Elements

As the lab experiments have shown, maintaining inter-element isolation through sidelobe suppression and reduction of acoustic and electrical crosstalk will be critical to overall image quality. Typically in an array design, a common ground plane and matching layer are used. Previous modeling has shown the need for a ground wire to each element and individual matching layer caps to reduce acoustic crosstalk below -50 dB. The array manufacture and interconnect scheme become more difficult with these constraints. New technologies will need to be developed to reliably take 20,000 element leads through the acoustic backing layer and array kerf filler without interfering with the acoustic performance.

Experimentation and modeling have also shown the need for a composite array design. At 3 MHz, a 1 mm diameter transducer element operating in thickness mode has a width to height ratio near unity. Because the ratio is near unity, attempting to excite the element in the thickness mode will also excite other lateral modes. In the laboratory, this resulted in an element with the theoretical main lobe width and good sensitivity, but high first sidelobe levels near -6 dB. A composite approach will sub dice the 1 mm elements into some number of very thin elements such that each element will have a width to height ratio of at least 2.5 thus avoiding the range where inter modal coupling occurs. Figure 15 demonstrates the concept.

Once an array is developed with a suitable method for getting the signal lines out, the electronics must be capable of processing 10,000 beams worth of data in real time and with low power consumption. A small scale prototype is planned for testing different approaches to the problem.

Acoustic Lens Technology

Due to the physics of diffraction, sidelobes exist for a spherical aperture that fall off as the Bessel function. Because the system concept calls for a retina which transmits and receives through the same spherical lens, the diffraction pattern will fall off as the Bessel function squared. Still, even for the on-axis beam the theoretical sidelobe levels will only be -35 dB down. For most sonar systems that would be acceptable. For an imaging sonar with target features varying by as much as 50 dB from point to point, lower sidelobe levels will reduce image smearing from specular reflectors. An aperture shaded lens concept is under investigation where a lossy material such as nylon is molded across the polystyrene element. The nylon element is thicker at the edges than at the center so the edge rays are attenuated more. Currently the machinability, attenuation, density, sound speed, and temperature dependence characteristics of various materials are being measured. Prototype lenses will be built from the most promising candidates.

Acoustic lens research is also being conducted in compact focal length designs. Current flat focal plane lens designs with 25 degree fields of view require focal distance to aperture diameter ratios (f numbers) near 2.5. For a 15 cm aperture lens, that translates into a 38 cm focal distance. If the beamforming volume is 15 cm diameter x 38 cm tall, squeezing the rest of the system components into a diver-held sonar will be difficult. Some early modeling indicates f1.5 lenses are possible which would reduce the volume to 15 cm diameter x 23 cm tall; a 40% volume savings! Different materials and concepts are being evaluated. This research will be rolled into the sidelobe reduction effort. A compact aperture shaded lens design for a diver-held sonar will be the end result.

CONCLUSION

A research program in the classification of suspected

mine targets in highly turbid water has been presented. The technologies being developed should benefit UXO classification jobs in these murky waters as well. The objects of interest to UXO clearing agents will be smaller than the targets presented here, but resolution down to 1 cm^3 has been demonstrated. The technologies being developed should have application to underwater UXO classification. A diver-held or ROV mounted sonar with the classification capability that has been demonstrated in the laboratory will exceed the performance of any diver-held sonar that is currently commercially available.

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DETECTION OF UXO WITHIN A SAND BORROW OFFSHORE OF SEABRIGHT, NEW JERSEY

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INTRODUCTION

The U S Army Corps of Engineers (USACE) and the state of New Jersey are presently engaged in constructing the largest beach restoration project ever undertaken in the United States. The purpose of this project is to protect twelve miles of the heavily eroded and highly developed north Jersey shore from coastal storm damages. The total cost of the project is estimated at $1.678 billion (Federal and non-Federal costs). The primary source for the required beach quality sediment is an approximately 6 square mile area located 3 miles offshore of the southern end of Sandy Hook (Figure 1). Ocean-going hopper dredges excavate sediment (initial project construction total of 18.5 million cubic yards) from the authorized borrow area and, with the assistance of nearshore pump-out facilities, transport the material onto the beaches. Project construction started in 1994. There is 50-years of continuing life-cycle beach renourishment programmed into this project.

Within a very short period, items of ordnance were discovered on the newly constructed beaches. Expensive clean-up operations were required to locate and remove ordnance from the beach. The source of this material was determined to be ordnance mined along with the borrow, although there had been no pre-project data suggesting the presence or the extent of this ordnance contamination. To eliminate further risk of ordnance indigestion, the project dredges where fitted with 1.5" square grates over the dredge dragheads. These grates prohibit excavation of the ordnance, thus protecting the dredge and the resultant beach area from UXO (unexploded ordnance) contamination. However, the installation of the draghead grates also reduced the efficiency of the dredging operation by an estimated 20%. Over the 50-year continuing construction project life the presence of these grates and the reduced dredging efficiency could cost hundreds of millions of dollars in lost productivity.

BACKGROUND ON FORT HANCOCK

Coastal fortifications and military posts have been located at the northern end of Sandy Hook, NJ since the mid 1700's. This strategic location guards the major navigation routes into New York Harbor. Construction of Fort Hancock began in 1857 and by 1874, Sandy Hook was designated as the Army's first proving grounds for munitions and weapon testing. Various generations of large shore-based coastal artillery and mortar batteries were built at Fort Hancock at the north end of the sand spit, Figure 1. Remanent of the fortifications constructed from the 1890's until the 1940's are still in place at this Formerly Used Defense Site (FUDS) and maintained by the National Park Service. From 1874 until World War I, a four mile stretch of beach and coastal dunes and offshore areas were used as target locations for the nation's primary artillery proving ground. Various naval and army artillery and experimental rounds were tested along with proof firing of barrels for government acceptance. From the 1890's until the late 1940's nearly every summer the crews of the large caliber coastal artillery and mortar batteries from Ft. Hancock and other installations practice fired into offshore impact areas. This long term use of Sandy Hook for military training and artillery proofing has resulted in ordnance contamination of large sections of Sandy Hook proper and the nearshore (USAED, St Louis 1993). A wide variety of ordnance (light artillery to 15 inch cannonballs) dating from the Civil War through World War II have been, and are currently being, recovered from Sandy Hook and adjacent areas. The entire

offshore sand borrow area is within the quoted firing fans and range potential for most classes of artillery installed or tested at Fort Hancock. Discussions with EOD (Explosive Ordnance Demolition) Team members at Fort Monmouth (Army) and Earle Naval Air Station (NAS) confirmed that the age and caliber of recovered ordnance pieces from the general vicinities of interest suggest that Fort Hancock is a likely source for the bulk of this material. They referenced finding assorted Civil War era cannonballs, Parrot rounds, an selection of 3-inch hollow shells, 10-inch munitions filled with ball bearings, etc. all which were known to be tested at Fort Hancock from 1875-1919. An array of coastal artillery ordnance were disclosed during limited bottom raking operations in the borrow area. This included 6-, 8-, 10-, 12-, and 16-inch diameter projectiles. The most common calibers were 8- and 10- inch coastal artillery shells.

STUDY OVERVIEW

To investigate the possibility that more efficient dredging can be conducted in certain areas of the borrow or if the ordnance fields may be suitable for efficient clean-up operations, it was necessary to characterize the degree of ordnance contamination. The challenges of mapping an underwater ordnance contamination field are significant and one which has received recent attention at other USACE projects (Pope, Lewis, Welp, in press; Welp, et al 1994) and within the military research program. A review of available and emerging technologies was made and a offshore geophysical survey designed with the intent of testing several geophysical and oceanographic techniques which might be suitable for use at the Sea Bright borrow.

Equipment adapted and mobilized to the project site included a research vessel with GPS positioning, two underwater video cameras, two acoustical systems, and a Cesium vapor magnetic gradient instrument. In addition, a number of inert pieces of ordnance were used on site for controlled calibration testing of the equipment. The underwater video system and two acoustical systems were "off-the-shelf" items which required no further development for their use at this site. The two acoustical systems included a high frequency side scan sonar and sweep-frequency subbottom profiler. Some field experimentation and modification was conducted to improve system deployment and evaluate the performance of each system in detecting ordnance-like objects. Most of effort during this pilot study was expended in adapting a state-of-the-technology, underwater deployable/towable, Cesium vapor magnetic gradient instrument. Prior to site deployment this involved the design and fabrication of a water-tight tow containing the magnetometers, integration with an altimeter for controlling elevation, and associated data processing software.

Inert Ordnance Test Bed

An ordnance calibration and test field was temporarily installed in a protected cove adjacent to the Sandy Hook Coast Guard Station. A jet pump was used during low tide to bury (approximately 0.7m below the sand surface) pieces of inert ordnance. An additional line of 9 pieces of inert ordnance of various calibers placed 3 meters apart was installed parallel to shore at a location where approximately 2-to-2.3 meters of water would exist during high tide. Each ordnance target was marked with a witness buoy. Prior to the installation of the ordnance test bed, the area had been "swept" with a hand-held magnetometer to confirm that no other ferrous metal objects were present. The magnetic gradient instrument and the acoustical profiler were towed over this test bed a number of times during high tide to evaluate the performance of these two instruments in a controlled test. After completion of these tests, the inert ordnance was removed from the site and it was returned to its pre-test condition.

ACOUSTICAL SYSTEMS

Side Scan Sonar

The Side Scan Sonar was used during the Pilot Study for several purposes; to provide a general "picture" of the geology of the site including bedforms, note large obstructions which may need to be avoided, and to test it's capability to detect small (ordnance-type) objects on the bottom. The latter goal would require identifying a pattern of returns in a specific area that was more likely to be a cluster of hard, cylindrical objects than normal returns from bottom roughness elements. Throughout the survey area there were hard, dark targets that appeared on the Side Scan Sonar

records as small as 0.25m long which had relatively high back scatter signals. Without additional ground-truthing it is not appropriate to identify these returns as pieces of ordnance. Larger objects with patterns that were likely of man-made origin were observed in the study area. These included what appeared to be a small sunken boat partially buried and a subsurface buoy. The Side Scan Sonar did a satisfactory job in locating larger objects and illustrating changes in bottom texture, but it is not appropriate as an instrument for independently detecting the classes of ordnance present at this site. As with all applications of Side Scan Sonar, a full-survey use of this instrument would need to include a "ground-truthing" phase where divers or other sources of bottom imaging would be collected and used to verify record interpretation.

Sweep Frequency Subbottom Profiling

The purpose of testing the subbottom sweep frequency profiling was to determine the bottom material characteristics and investigate any ability of this instrument to detect hard return objects buried within the upper (say 2 meters) portion of a sandy bottom. The potential value of subbottom acoustical profiling in characterizing the ordnance contamination at Sea Bright would be realized if it was able to document whether or not suspected ordnance was buried beneath the sand surface which would complicate any perspective site clean-up activities. As the first step in testing the subbottom acoustical profiler was towed several times approximately 1 to 2 meters above the inert ordnance test bed. Targets were detected which may be interpreted as representing the ordnance located on the bottom. However, nothing could be detected from the test bed inert ordnance which were buried by sand jetting. Since a return from the buried ordnance in this setting could not be detected, it is concluded that the scattering of the acoustical signal by the sandy sediment prohibits the competent use of this method to positively identify buried ordnance targets. The conclusion of the initial study is that acoustical profiling would be of limited use for ordnance detection below the ocean bottom. However, ordnance near the sea-bottom boundary may be resolvable.

Both acoustical systems did provide a great deal of data concerning the site material texture and indicated the presence of on-the-bottom hard target returns. However, interpretation of these targets as ordnance is not appropriate without verification via ground-truthing or characteristic magnetic responses.

VIDEO CAMERA

Two types of underwater video camera deployments were tested. The CERC Remotely Operated Vehicle (ROV) is maneuverable and contains an underwater video camera. In addition a higher resolution, low-light camera was brought on site for testing. The low-light camera was deployed via mounting on the ROV and on a towable v-fin. Video image observations revealed the bottom in the inspected borrow areas to be sandy with some rhythmic topography (sand ripples) and occasional coarser sand/gravel streaks. Several pieces of presumed ordnance were observed.

MAGNETIC GRADIENT INSTRUMENT

To detect the presence of ferrous dipole targets of finite length, a marine cesium vapor magnetic gradient instrument was developed and deployed. This instrument had a noise level of about 0.015 nanoTeslas/meter or about 5X less the magnetic gradients generated by relatively quiet coastal wave action. Numerous clusters were identified which contained responses typical of the anticipated ordnance items. The magnetic gradient instrument demonstrated a high degree of ferrous object sensitivity, thus providing a large detection range and target location capability. Potentially the gradient data can be used for basic classification and discrimination of ordnance size.

Magnetics Introduction

Underwater magnetic investigations to detect ordnance were conducted in the Sandy Hook area at a constructed test site, an ordnance disposal site, and at a designated borrow area. The principle of magnetic detection and location of the ordnance originates from the localized magnetic field variations that these objects produce. These deviations from normal magnetic field conditions are the result of specific characteristics of the ferrous material (iron and steel) contained in the manufactured ordnance. Two physical features

are present in ferrous material which in turn causes a change in the local magnetic field. These properties are: (1) Induced Magnetism. This is the principle phenomena that makes most ferrous metal ordnance detection and classification possible with magnetic surveys. The Earth's magnetic field establishes a secondary magnetic field in the ordnance item. This disturbance is measurable when a sensor is within the area of the ordnance's magnetic signature. The intensity and range of the local magnetic field alteration is based on the magnetic susceptibility of the iron or steel and the size and shape of the shell. If this value is known, the size of the ordnance can be estimated and the caliber roughly approximated. (2) Remanent Magnetism. This is the natural magnetic field that the ordnance material contains. It is a function of the properties of the metal and the casting procedure. Both of the above properties form the basis whereby various sizes and types of ordnance may be detected. Currently, few measurements have been made to determine what these values are for WWII and earlier ordnance items.

Magnetic Gradient Instrumentation

To accurately and rapidly detect the magnetic field variations produced by ordnance, a much more precise magnetic sensor is used than commonly employed in typical terrestrial and marine surveys. The instruments used for the Sandy Hook investigation were State-of-the-Art cesium vapor, marine magnetic gradient sensors produced by Geometrics of Sunnyvale, CA. These were fabricated and configured expressly for this project in a development effort. For marine detection and location of UXO it is necessary to deploy Cesium vapor magnetic sensors or some other extremely precise instrument which have a sensitivity of +/- 0.02 nanoTeslas or better. This aids the discovery effort in two ways. (1) Smaller sized objects can be detected. (2) It is possible to measure the principle gradients of the anomalous magnetic field. These measurements can be used to effectively vector toward the target object. From several locations, the dipoles of a target location can be established by the intercepts of the gradients. In this investigation two Cesium vapor magnetometer were towed about 55 meters behind a fiberglass hulled research vessel at a depth of 1 to 2 meters above the ocean bottom. The magnetic gradients were determined by sensors which were mounted 2 meters apart. The following data were collected every 2 seconds: (1) Time. (2) Ship's position. (3) Instrument set back. (4) Instrument Altitude from the sea bottom. (5) The Course Over Ground (COG). (6) The Speed Over Ground (SOG). The following were recorded every 0.1 Second: (1) The magnetic field at all sensors. (2) The horizontal magnetic field gradient. As a consequence of measuring the magnetic gradient, it was possible to immediately determine if an ordnance type signature originated from the port or starboard side of the track line.

Test Site

The magnetic gradient instrument was then towed over the calibration site, Figure 3. In this test the magnetic sensors or 1 meter above the bottom and the inert ordnance items. The individual and the cluster inert ordnance targets were detected in various calibration passes over the test site. In most tests the signature of adjacent items overlapped, since the area of magnetic disturbance exceeded well beyond 2.5 meters. However, it was still possible to distinguish the individual presence of seven to nine items from the magnetic gradient data in every instrument pass through the test area.

Small Site

A small offshore location were previously found ordnance had been place was investigated, Figure 4. Multiple traverses were made over this site. The water depth at the time of the investigation was nominally thirty feet. This designated ordnance placement site was about 75 by 90 meters in size. Multiple passes over this site and immediate adjacent areas, detected numerous ordnance type magnetic and magnetic gradient signatures, Figure 5. During all of these short traverses, the Cesium vapor magnetic sensors were "flown" 1 to 2 meters above the sea floor. All of these detected responses are indicative of short magnetic dipole type targets, typical of the expected ordnance that had been placed at the location. However the magnetic responses of many of the objects were suggestive of a dipole in a rather random orientation. This would be expected for ordnance items placed on the site in a relatively recent time frame. It comparison, the magnetic investigation of the borrow site using rather long traverses, revealed that for the most part the ordnance item appear to have become

aligned in the long axis parallel to the shore. This preferred orientation has been observed in other near coastal beach environments.

Long Lines

Five traverses which stretched several miles in length, were collected in north-south directions at adjacent separations of 200 feet, Figure 6. These lines were immediately west of the borrow area termed "1A". Adjoining track lines were conducted in opposite directions, i.e north to south which was adjacent to south to north, etc. The instrument package was located at a 170 foot set-back behind the vessel and it was flow at an elevation of 3 to 6 feet (1 to 2 meters) above the sea floor bottom. Significant concentrations of ordnance sized objects were encountered throughout these passes, Figure 7.

The spatial distribution of magnetic responses along the traverses were indicated on special plots, Figure 8. The areas along the tract where a magnetic response was evident is darkened. This practice shows any 2-dimensional distribution of ferrous objects in the investigated area, and allows for discrimination of large vs smaller objects. A positive gradient anomaly in this figure represents a magnetic object east of the line while a negative response is generally indicative of an object west of the line. A larger object will have a longer segment of the tract where a magnetic disturbance is recorded. Some evidence suggests that the density of the magnetic objects diminishes significantly at the southern end of the surveyed area.

The collected data gave a very close representation to the total horizonal magnetic gradient since the gradient was known both traverse and parallel to the track lines, Figures 9 to 12. This gradient, either negative (dashed lines) or positive (solid lines) was used to vector toward and triangulate upon the pole and dipole locations of various ferrous objects. Three graphics are generated for each anomaly, the upper left is the total anomalous magnetic field (in nanoTeslas X 10^4) as measured by the two Cesium vapor sensors separated by 2 meters traverse to the track line of the vessel. Sensor "A" is to the left or port of the course and sensor "B" is to the right or starboard of the trackline. The right side of the plot is to the south or north as indicated by "S" or "N" in the caption over the figure. With only a few exceptions, the majority of the detected magnetic objects have a magnetic "low" response to the north of the magnetic "positive" response. In the northern latitudes such as a location of New Jersey this is indicative of the anomalous magnetic effects originating from mainly the induced magnetic field effect and only a smaller portion being from remanent magnetization. The horizonal magnetic field gradients are displayed in the lower left part of the figure. These are "G" "east-west" gradients (perpendicular to the track line) and "H" north-south" magnetic gradients (parallel to the track line). Both measurements are in nanoTeslas / meter. The right plot on each figure displays the smoothed track line. The portion of the track line which is inclusive of the detected anomaly is plotted in relative northing and easting locations (units in feet). The intensity and horizonal direction of the resultant magnetic gradient is then plotted in reference to the smoothed Course Over Ground (COG). In these representations the length of the magnetic gradient vector is proportional to the strength of the gradient. Since the target objects can respond as dipoles (each generates a positive [south end] and negative [north end] magnetic anomaly) the gradient vector from the track line is dashed in its decreasing direction and solid in its increasing direction. This is necessary since a magnetic low anomaly on one side of the track line can have the same gradient as a magnetic high on the opposite side. However, as the sensors pass by the anomaly, the gradients will converge on the source location. From this method, ordnance type dipole objects can be even further identified, by the location of a magnetic negative gradient (dashed lines) generally immediately northward of a magnetic positive gradient (solid lines).

Almost all of the detected magnetic responses within distances of about 15 feet or each side and beneath the Cesium vapor magnetic sensors were locatable. This gives a detection and location swath width of about 25 feet for survey purposes. Over 95% of the detected anomalies were determined to within apparent X-Y locations of a few feet. The major exception to plotting an object's position occurred when the target was located in a major marine debris field and was in a complicated magnetic gradient environment. Many of the objects are most likely elongated dipole objects (much like a 3 to 4 foot long, 10

inch diameter shell would be). These type of items could very easily be situated so that a convergence of negative magnetic gradients would be immediately (5 to 10 feet) north of the convergence of magnetic positive gradients.

Additional Data Processing

A portion of the magnetic gradient data were processed by Arete Engineering Technologies Corp. (AETC) using Maximum Likelihood Estimation techniques to determine the location (along- and cross-track position and depth below the ocean floor) and the sizes of the target. For these data analysis, the ordnance was assumed to have no remanent magnetization and be a magnetic dipole, elliptical in shape. The collected data were then best fit to the magnetic field generated by a target algorithm. To achieve the best fit, various target orientation geometries, depth and distance to the target, and the average radius of the target size were automatically varied. This proved to be a robust method of computing the position, depth and size of the target object. Based upon analysis of these data, it is determined that the system detects targets over a cross-track swath of twenty-five feet, and the density of targets is about one per 100 x 100 foot square. The computed spread of target sizes (2 to 16 inches) and the average calculated target size (8 inches) is very similar to the range (3 to 16 inches) and most common ordnance size (10 inches) recovered from bottom raking operations. About 20 % of the targets appear to be resting on the bottom. Most of the rest are best fit at depths below the bottom of less than two feet. These data are significant in accessing the mobility of the ordnance in the coastal environment and for any clean-up efforts.

CONCLUSIONS

The cesium vapor magnetic gradient instrument proved superior to any other tested technique in locating the UXO targets in the marine environment. Noise levels of 0.015 nanoTesla/m were achieved. This is about 5 times less than the magnetic gradient of very low coastal sea states.

The magnetic response UXO appears as simple dipoles which can easily be discriminated from marine debris. The effective swath distance for detecting the ordnance was about 15 feet to each side of the sensors. The vast majority of the ordnance was locatable in apparent X-Y position to within a few feet. Modeling of the data suggests that most of the UXO is either on the surface or buried within a few feet of the surface.

The Seabright field investigation proves the technical viablity of using a Cesium-vapor magnetic gradient instrument for detecting underwater UXOs.

ACKNOWLEDGEMENT

The Seabright field test and data analysis was conducted under the sponsorship of the US Army Engineer District, New York. Permission was granted by the Chief of Engineers to publish this information.

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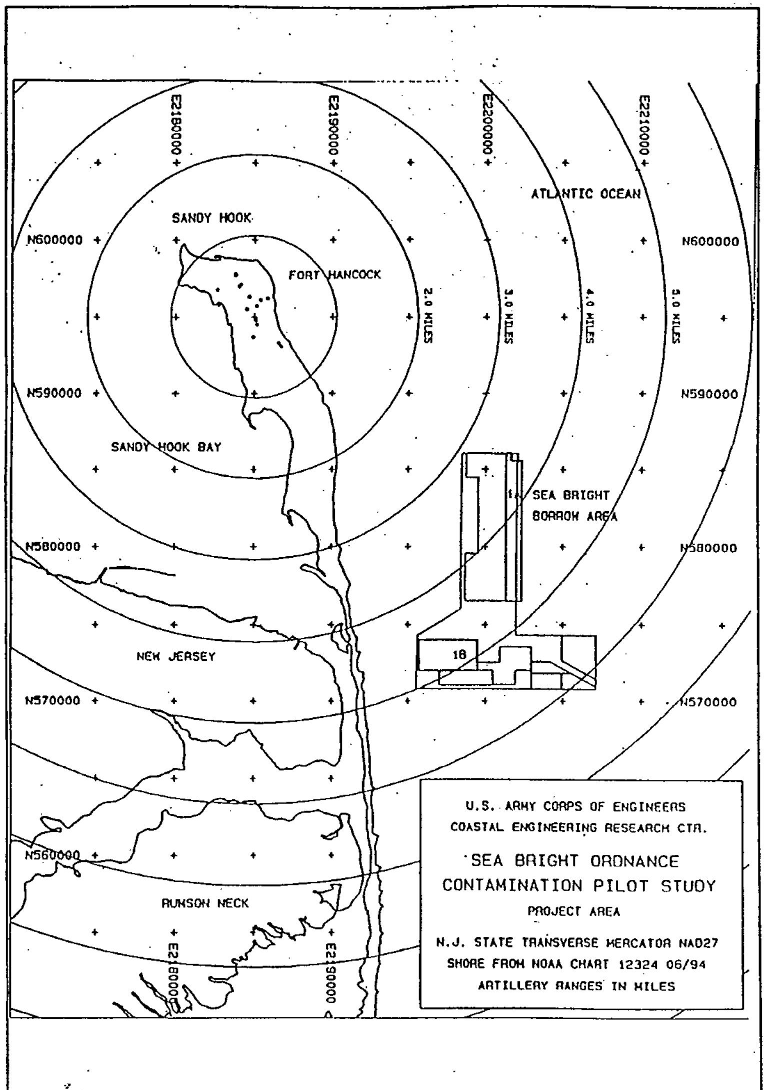

Figure 1. Location map of Seabright borrow area relative to Fort Hancock.

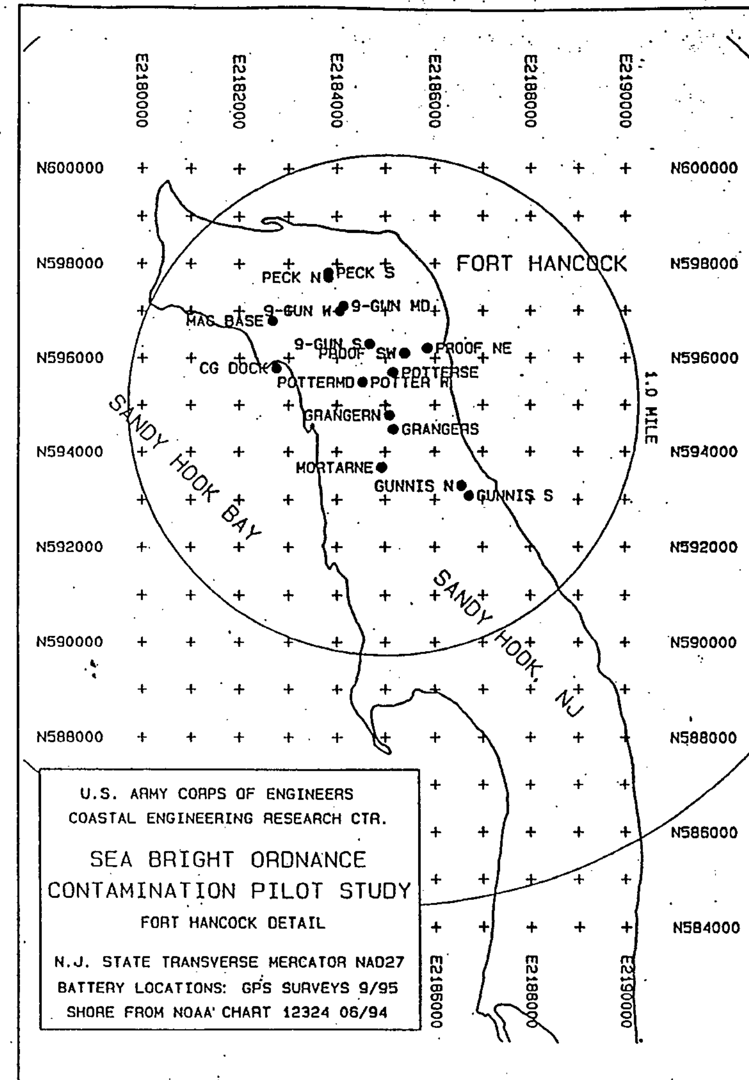

Figure 2. Fort Hancock batteries.

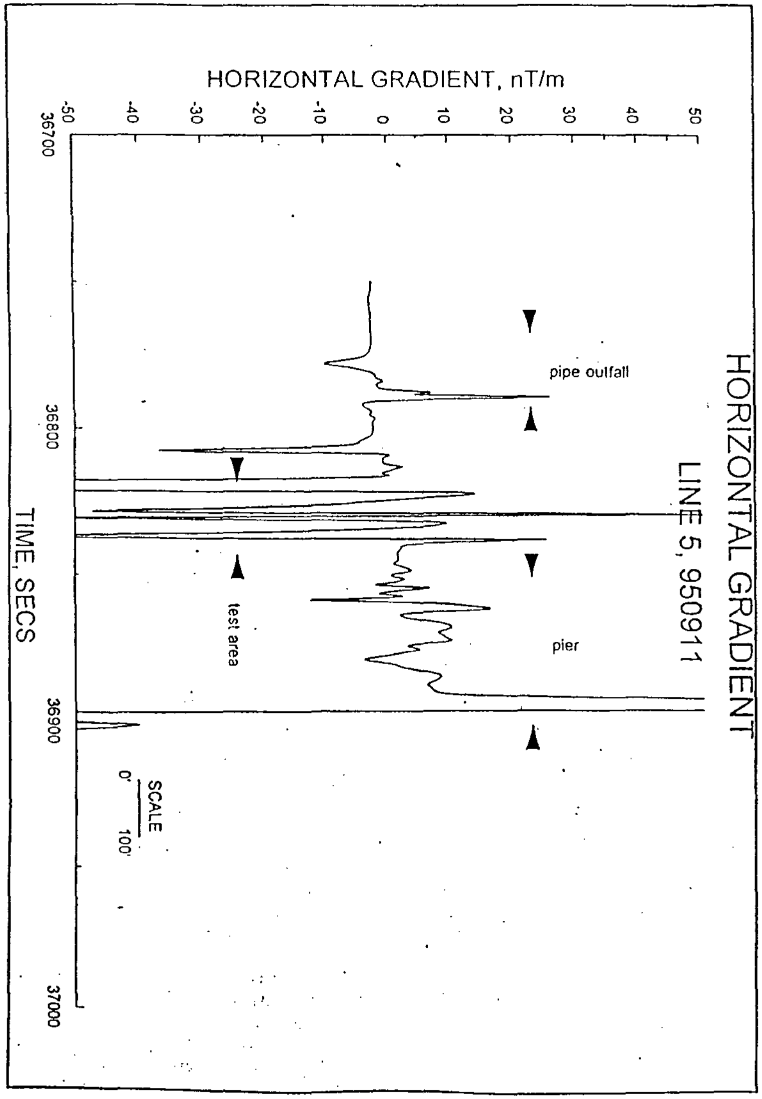

Figure 3. Example of horizontal magnetic gradient recorded during calibration tests with inert ordnance test targets. Pass number 5.

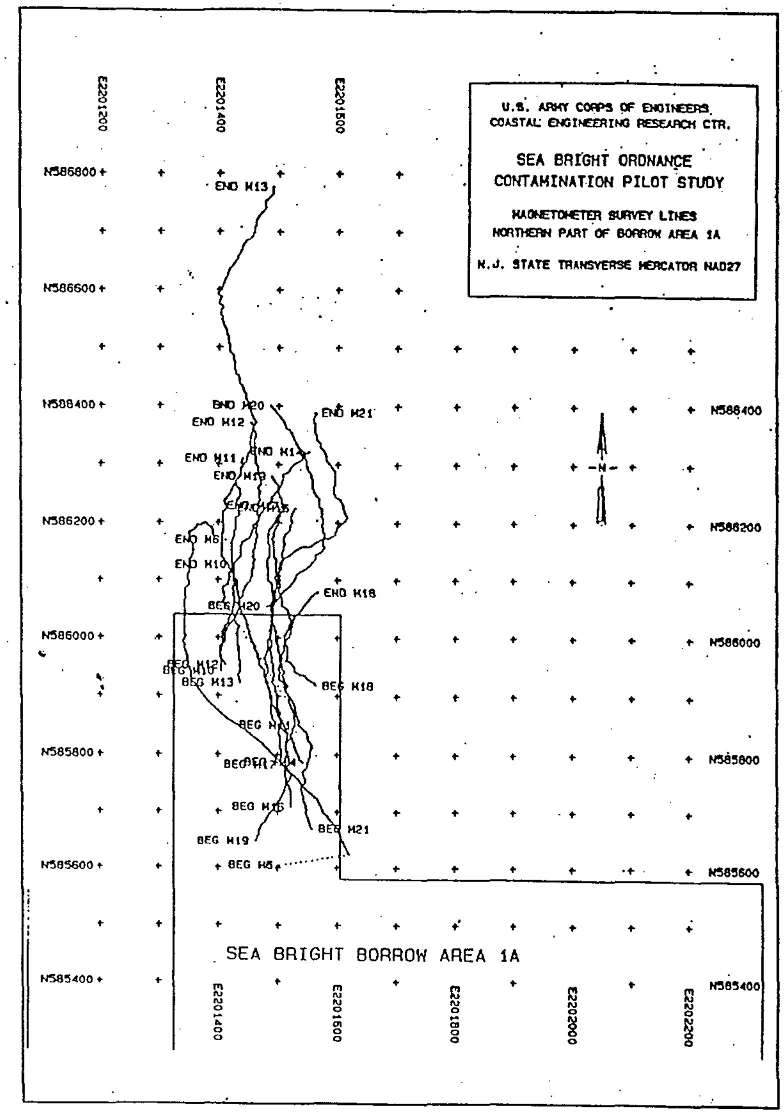

Figure 4. Magnetometer survey lines, northern portion of borrow area 1A.

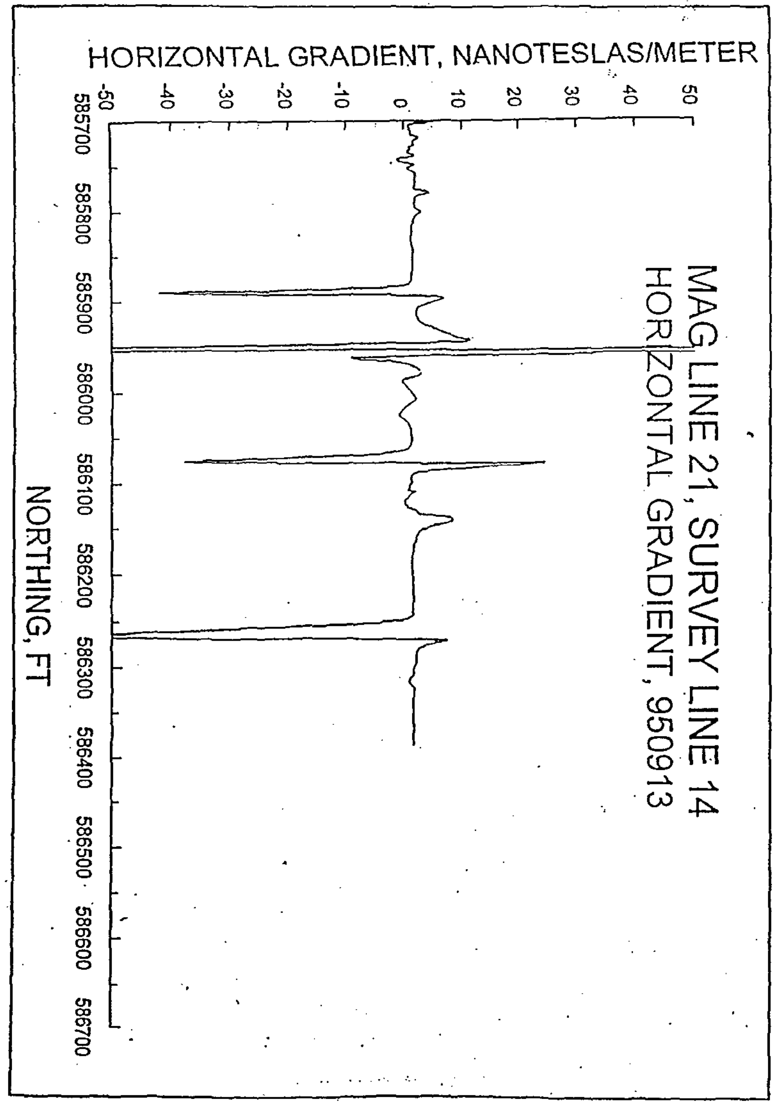

Figure 5. Horizontal magnetic gradient recorded in ordnance disposal area. Line 14.

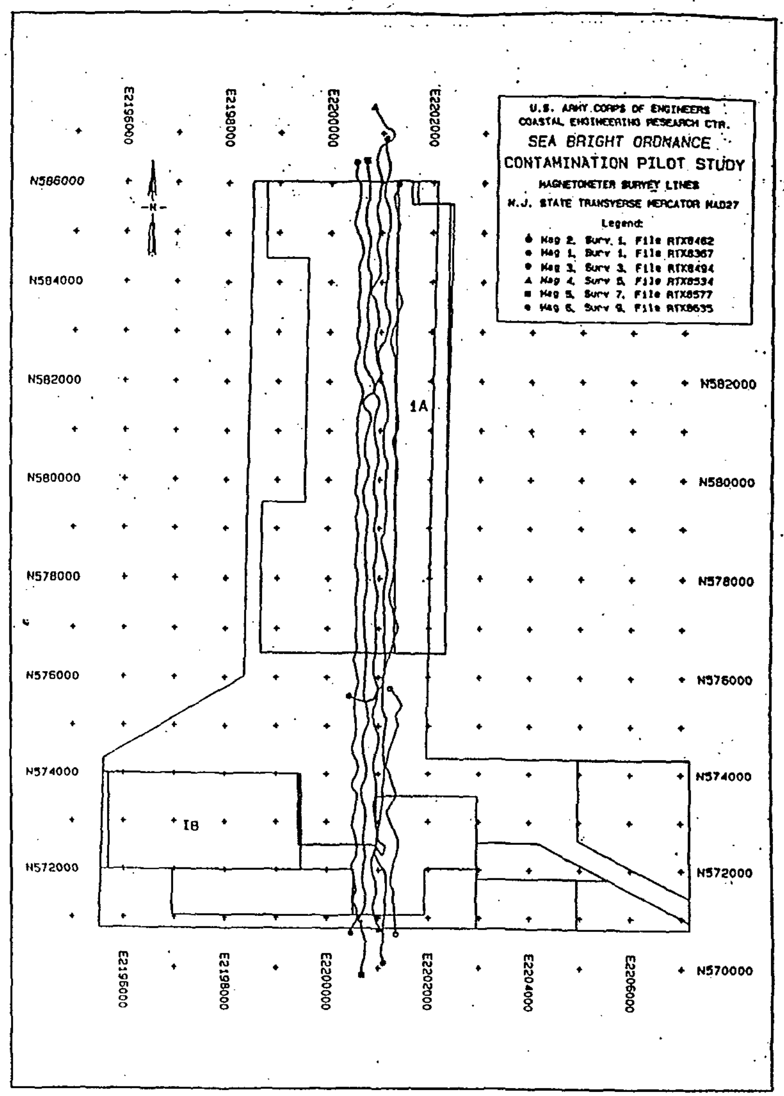

Figure 6. Long magnetometer survey lines. Overall Seabright borrow area shown for reference.

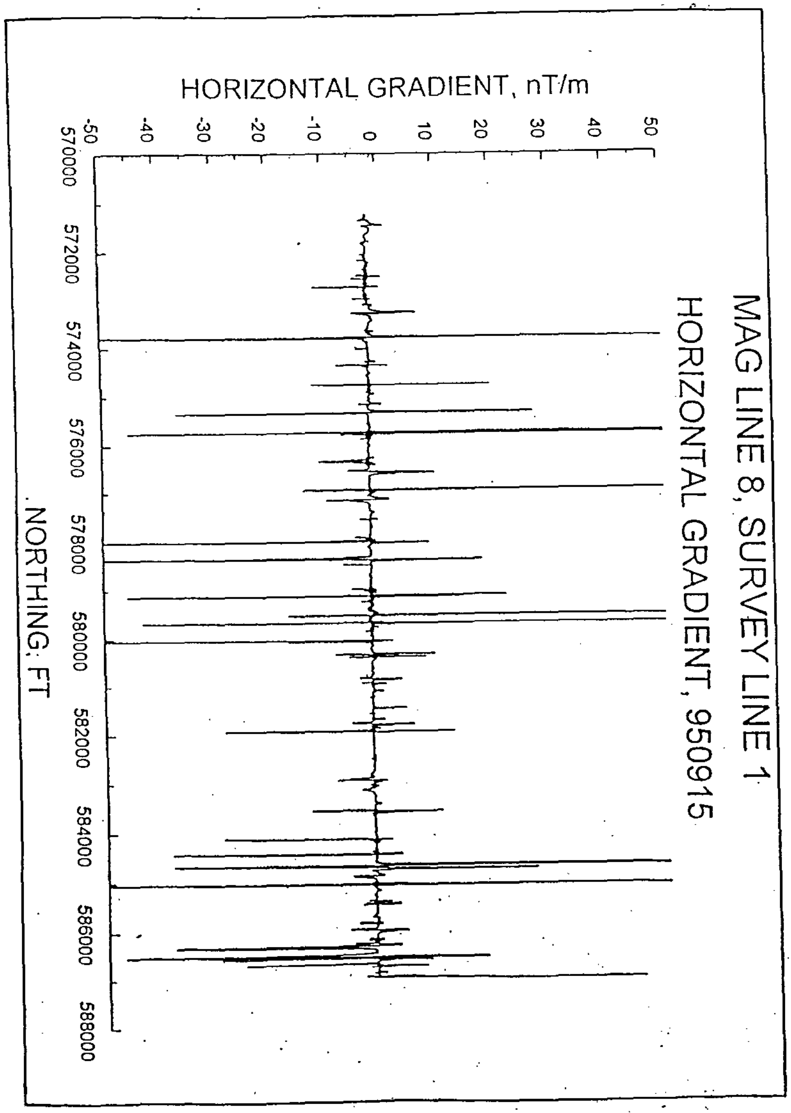

Figure 7. Horizontal gradient recorded on long magnetic traverse number 8. X-axis represents State Plane coordinate.

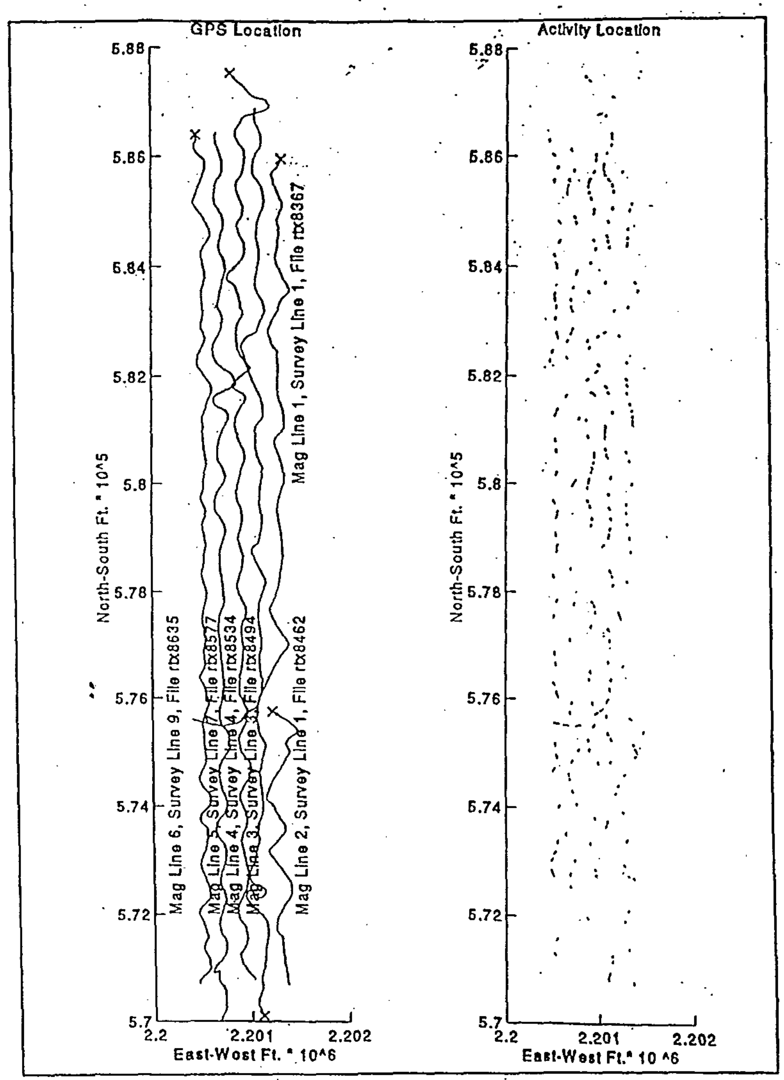

Figure 8. Plot of long magnetic traverses showing truck lines on left and zones of magnetic response on the right. Scales are in feet measured from arbitrary zero points - locations do not represent State Plane coordinates.

EVALUATION OF THE USE OF EXISTING MARINE GEOPHYSICAL REMOTE SENSING SYSTEMS FOR THE MAPPING AND CLASSIFICATION OF UNEXPLODED ORDNANCE IN COASTAL WATERS

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ABSTRACT

During the summer of 1995, the Naval Facilities Engineering Service Center (NFESC) established a highly calibrated Unexploded Ordnance (UXO) test range offshore the Pacific Missile Range Facility (PMRF), Barking Sands, Kauai. The objective of the range was to provide an area that could be used to validate the performance of commercially available geophysical sensing systems for the mapping and classification of underwater UXO. The range included a calibration site and an operational site, and covered an area of 5.3 square kilometers. A total of 257 inert ordnance pieces and 41 false targets were precisely placed on or under the seafloor in water depths from 1 to 50 meters. Targets ranged in size from groups of 7.62-millimeter cartridges to single Mk83 (1,000 pound) bombs. The University of Hawaii Marine Minerals Technology Center (MMTC) led the demonstration effort on the range. NFESC performed the preliminary scoring, crediting the demonstration team with finding 17 of the 145 targets installed within the area they surveyed.

This paper discusses the range design, installation, recovery, demonstration and preliminary results of scoring.

INTRODUCTION

The Naval Facilities Engineering Service Center (NFESC) was tasked by the Environmental Security Technology Certification Program (ESTCP) to investigate the applicability of marine geophysical remote sensing systems for the mapping (detection/ location) and classification of Unexploded Ordnance (UXO) in coastal waters. ESTCP's goal is to demonstrate and validate the most promising innovative technologies that target the Department of Defense's most urgent environmental needs and that are projected to pay back the investment through cost savings and improved efficiency.

The criteria used to evaluate the demonstration effort were modeled in part from similar (land) work conducted at the Jefferson Proving Ground during the Unexploded Ordnance Advanced Technology Demonstration Program (references 1 and 2).

The approximately 5.3 square kilometer offshore test area used for this project was designated the Seafloor Target Mapping and Classification (STMC) range. The STMC range was divided into two areas: 1) the demonstration area; and 2) the calibration area. The calibration area was designed to provide the demonstration team with specific targets at known locations so they could prepare for their demonstration. The location and classification of targets in the demonstration area were not provided to the demonstration team.

Due to the distinct possibility of losing targets because of storms typically experienced off Kauai during the winter months (very large surf and high degree of sediment transport in the range area), recovery of the targets was performed immediately following the demonstration operations.

The use of existing technology, as proposed, may allow for a quicker and more cost effective cleanup of offshore UXO contaminated areas. However, the intent of this project was exclusively to evaluate underwater mapping and classification systems. No investigation into the actual cleanup of UXO was conducted.

BACKGROUND

Many coastal marine areas have been used over extended periods by the United States armed services and allies for simulated warfare training using live ordnance. The recent reduction of defense requirements has resulted in the termination of selected live ordnance

training activities. However, large numbers of potentially dangerous ordnance still remain on or in the seafloor. Cleanup of UXO contaminated coastal land areas and their surrounding waters is now required before these areas can be returned to public use. Before contaminated areas can be cleared, effective means to map and classify subsea ordnance must be developed and demonstrated.

STMC RANGE LAYOUT

Kauai is the northernmost island of the Hawaiian windward islands and fourth largest of the eight major islands in the southeastern part of the archipelago. PMRF, Barking Sands is located along the western shore of Kauai. Figure 1 shows the layout of the STMC range.

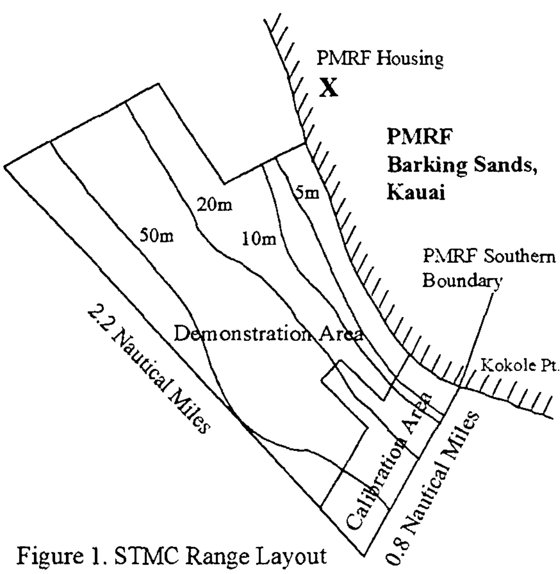


Figure 1. STMC Range Layout

The range ran approximately 4.0 kilometers along the PMRF, Barking Sands shore, and extended approximately 1.5 kilometers to sea. The shallow water area of the range stopped south of PMRF housing so that project operations did not interfere with the summer beach and near shore swimming activities in this area. The portion of the range that was offshore from the housing area started approximately 0.9 kilometers off the beach at a water depth of approximately 15 meters. The southern end of the STMC range stopped at the southern boundary of PMRF. Water depths in the project area ranged from 1 meter to just over 50 meters. As shown in Figure 1, the calibration area of the range was located in the southern most section of the range, from shore out to just beyond the 50-meter contour.

The surface area of the entire STMC range was approximately 5.3 square kilometers. The surface areas of the calibration and demonstration areas were approximately 0.7 square kilometers and 4.6 square kilometers, respectively.

Target Placement Database

In the calibration area, targets were placed at evenly spaced positions, and were arranged along straight lines. An algorithm was written to randomly place the targets within the demonstration area, estimate the water depth of each target position based on the position of the target with respect to contour lines, and randomly assign a target type to each position. Range installers imported the database into the installation navigation systems as navigational waypoints. They plotted installation position for each target as a visual reference check during installation.

Calibration Area Target Distribution.

The targets in the calibration area were installed in quantities, types, and patterns designed to facilitate the calibration of the demonstration instruments that were used. Figure 2 shows the shape of the calibration area and the locations of each target.

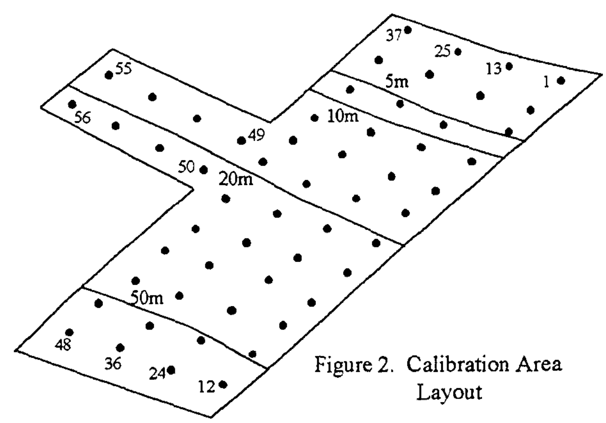


Figure 2. Calibration Area Layout

Fifty-six targets (15 different types or classifications) were installed in this area. The spacing between adjacent targets was approximately 100 meters. As can be seen in Figure 2, four rows of 12 targets each were installed from 1 meter to just over 50 meter water depths in the large rectangular portion of the calibration area. Each row contained targets of similar size and weight classification (at various water depths). The small rectangular portion of the calibration area contained various sized targets, but each were at relatively the same water depth.

All planned and as-installed data pertaining to targets in the calibration area were given to the demonstration team prior to the start of the demonstration activities.

Demonstration Area Target Distribution.

There were 193 randomly distributed target locations in the demonstration area. The inert ordnance items installed in this area were identical in type to the pieces installed in the calibration area, but greater in number. One hundred and fifty-two target locations were occupied by inert ordnance. Of these 152 locations, 23 contained groups of from 2 to 5 pieces. In addition, 41 false targets were installed and 10 inert ordnance pieces were buried. All information regarding the demonstration area targets was considered sensitive. This information was not given to the demonstration team until after completion of their final mapping and classification report. Table 1 provides a summary of how the targets were distributed in the STMC range.

Table 1. Target Distribution Summary

DISTRIBUTION DESCRIPTION	ENTIRE RANGE	CAL. AREA	DEMO. AREA
TOTAL NUMBER OF PIECES	298	56	242
INERT ORDNANCE PIECES	257	56	201
TOTAL TARGET LOCATIONS	249	56	193
INERT ORDNANCE LOCATIONS	208	56	152
FALSE TARGET LOCATIONS	41	0	41
GROUP TARGET LOCATIONS	23	0	23
BURIED TARGETS	15	5	10
WATER DEPTH			
* 1 - 2 METERS (WASH ZONE)	8	5	6
* 2 - 5 METERS	21	4	17
** 5 - 50 METERS	217	47	170

Note: * Very shallow water targets for airborne imaging system detection.
** Deeper targets for ship-operated sensing systems.

TARGET DESCRIPTIONS

Inert ordnance targets ranged in size from groups of 7.62-mm cartridges to single Mk83 (1,000 pound) bombs. False targets included various size steel or aluminum pipes, drums, chain, I-beams, box-beams, and grating. Sizes for the false targets ranged from 5.7-centimeter chain master links to 193-centimeter long pieces of 30.5-centimeter diameter pipe sections. Table 2 provides the name or description of each inert ordnance and false target installed in the STMC range. Multiple pieces of each item listed in the table were installed.

Table 2. Target Descriptions

INERT ORDNANCE	FALSE TARGETS
7.62-MM CARTRIDGES IN AMMO BOX	AMMO BOX (EMPTY)
20-MM CARTRIDGE	SMALL DRUM (SAND)
40-MM CASING	MEDIUM DRUM (SAND)
2.75-INCH ROCKET WARHEAD	LARGE DRUM (SAND)
5-INCH ROCKET WARHEAD	SMALL STEEL PIPE
7-INCH ROCKET BODY	MEDIUM STEEL PIPE
5-INCH 54-CALIBER CARTRIDGE	LARGE STEEL PIPE
5-INCH 38-CALIBER PROJECTILE	ALUMINUM PIPE
5-INCH 54-CALIBER PROJECTILE	BOX BEAM
MK106 PRACTICE BOMB	I-BEAM
MK76 PRACTICE BOMB	STEEL GRATE
FRAGMENTATION BOMB	CHAIN MASTER LINK
MK81 (250 POUND) BOMB	SMALL CHAIN
MK82 (500 POUND) BOMB	LARGE CHAIN
MK83 (1,000 POUND) BOMB	CABLE

NAVIGATION

Primary Project Support Vessel.

A Novatel Model #311R global positioning system (GPS) receiver was used for surface navigation on the 30-meter long M/V American Islander. This vessel is owned and operated by American Workboats, Honolulu, Hawaii. The receiver was set up as a mobile station and used in "differential mode" (DGPS). A Nautronix S04 Ultra Short Baseline (USBL) Acoustic Tracking System (ATS) was used for subsurface navigation and object tracking. A Nautronix mini-beacon served as a responder on a target deployment package during target installations, and on a ROV used for target recoveries. A KVH model 314AC Azimuth digital compass provided ship heading information and an ODOM Echotrac precision fathometer provided data regarding the water depth below the vessel. Pelagos Winfrog

integrated navigation software was used on a project computer to integrate surface navigation, subsurface navigation and tracking, fathometer, and compass data for real-time display and data storage.

Diver-Operated Inflatable Boats (Shallow Water Work).

A Motorola Model #LGT1000 GPS receiver was set up as a mobile station and used in "differential mode" for installing and recovering targets in the shallow water areas of the STMC range. The receiver, support instrumentation and power source (small 12-volt battery) were placed into a backpack to enable the system to be transported by one person. A 30-meter cable was attached between the GPS receiver and its antenna. The GPS antenna was held by one person over a plumbed surface float attached to an installed target while a second person operated the Motorola Model #LGT1000 to collect data.

DGPS Base Station.

The differential base station was a Novatel Model #3111R GPS receiver, set up in "fixed position" mode and outputting pseudorange corrections to the mobile DGPS systems via a Teledesign Model #TSI9600 radio modem. Identical radio modems were used with the mobile stations to receive the pseudorange corrections. The base station GPS antenna was set up adjacent to a surveyed brass disk on the pad for the PMRF Bore Sight Tower. Offsets from the GPS antenna to the brass disk were measured and accounted for in the setup of the shore station receiver.

Estimated Accuracy.

An analysis performed after completion of the project field work concluded that the accuracy of target placement positions was better than +/- 2 meters. The analysis used navigation instrument specification data and verification data collected while in the field .

TARGET INSTALLATIONS

General Approach.

The M/V American Islander supported target installations in water depths 10 meters and deeper. NFESC Navy dive personnel performed installations in water depths ranging from approximately 3 meters to 25 meters off small inflatable boats, and installations in the wash zone (approximately 1 meter deep) from shore. The wash zone targets were relatively small in size and weight, and were capable of being hand-carried out to the wash zone installation positions from a truck parked on the beach.

Installations off the M/V American Islander.

A specially designed deployment package was used on this vessel. The deployment package consisted of a steel frame that housed and protected an assortment of instruments used to observe and document the installations as they were taking place (Figure 3).

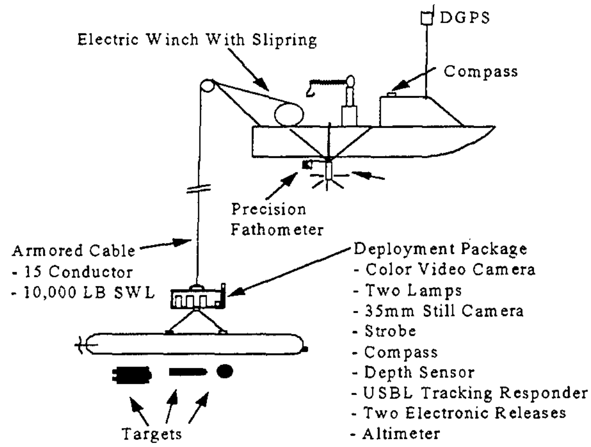


Figure 3. M/V American Islander Target Installation Components

The installation process was designed to maintain maximum control of the targets until release. Crew members lowered each target to the seafloor as the vessel held station.. Once satisfied with the drop location, they triggered one of two mechanical releases to place the target on the seafloor. The navigator then took a position fix immediately with the integrated navigation system, which automatically logged the water depth, target heading, and release time and took a 35-mm photograph. A total of 217 targets were installed in this manner.

Diver-Performed Target Installations, Anchoring, and Target Burials.

Divers lowered targets to the seafloor by hand from their inflatable boats. Once a target was on the seafloor, divers would descend and record target orientation and water depth, and video the seafloor and target. The target lowering line was then plumbed by the divers and a DGPS fix on a surface float attached to the lowering line was recorded. The lowering line was disconnected from the target before the divers returned to the surface.

Targets in the wash zone were anchored to the seafloor with a Manta Ray (small plate driven into the seafloor)

and also anchored on shore with 100-meter lengths of small diameter wire rope. The wire rope was used to relocate these targets during recovery operations. Plates were driven approximately 1 meter into the seafloor. Targets in 10 meters of water or less were also secured to the seafloor with Manta Ray anchors. A short piece of small diameter wire rope was attached between the target and the end of the anchor. Targets in water depths from 10 meters to 15 meters had small plastic plates (skirted anchors) attached to prevent targets from rolling on the seafloor because of surge or wave action; they were not otherwise anchored. Selected targets were buried in the seafloor. Burial depth ranged from 15 centimeters to 0.6 meter. A total of 32 targets were installed by divers; of these, 15 targets were buried.

TARGET RECOVERIES

The M/V American Islander supported the recovery of targets weighing over 90 kilograms and targets located in water depths 24 meters and deeper. Navy dive personnel recovered all other targets. The diver-performed recoveries were supported with two small inflatable boats and a Navy LARC-V amphibious vehicle. All but 11 targets were recovered. Seven of these were buried by over 3 meters of sediment on the beach and will be recovered when the sand moves offshore. Four targets, located in water depths greater than 10 meters were not found. In all other cases the targets were found directly below their logged position in the database.

DEMONSTRATION OPERATIONS SUMMARY

Demonstration equipment

The demonstration team used the M/V American Islander and the same navigation equipment that NFESC used for installing the range. The sensors used included the following:

- 100/500 kHz side scan sonar
- Multi-beam bathymetric sonar
- Phased array sub-bottom acoustic profiler
- Chirp sub-bottom profiler
- Airborne hyperspectral imaging system

MMTC used 4 days during their equipment set up time to become familiar with the integrated navigation system, provided by NFESC. Their familiarization included a 2 day training session conducted by the manufacturer of the system.

Schedule.

The planned and actual demonstration operations are listed below:

	Planned	Actual
Establish range	6 Jul-30 Jul	6 Jul-25 Jul
Conduct demo	31Jul-18 Aug	30 Jul-18 Aug
Verify Falsely Detected Targets	18 Aug- 24 Aug	Not done
Recover Targets	25 Aug- 23 Sep	19 Aug-15 Sep

The only significant departure from the schedule was the elimination of the recovery of Falsely Detected Targets (FDT). That operation was not done because the Quick Look Report of target positions could not be delivered by the demonstration team for reasons described below.

The demonstration survey required 19 days. As shown in Table 3, the time consisted of 7 actual survey days and 12 days for set-up, check out, analysis and repair of equipment.

Table 3. Detailed Demonstration Event

DATE (1995)	OPERATION	COMMENTS
07/30	Load/Setup Eq.	Equipment Load/Setup
07/31	Setup/Test Eq.	Equipment Setup and Test
08/01	Repair/Test	Side Scan Sonar Repair and Test
08/02	Repair/Test	Side Scan Sonar Repair and Test
08/03	Demonstration	Phase 2 - Swath Bathymetry
08/04	Demonstration	Phase 2 - Swath Bathymetry
08/05	Analysis/Setup	Map Targets/Reconfig. Equip.
08/06	Analysis/Setup	Map Targets/Reconfig. Equip.
08/07	Analysis/Setup	Map Targets/Reconfig. Equip.
08/08	Demonstration	Phase 3 - Cal. Area and Seismic
08/09	Demonstration	Phase 3 - Cal. Area and Seismic
08/10	Demonstration	Phase 3 - Cal. Area and Seismic
08/11	Analysis/Repair	Post Process /Repair Side Scan
08/12	Analysis/Repair	Post Process /Repair Side Scan
08/13	Analysis/Repair	Post Process /Repair Side Scan
08/14	Analysis/Repair	Post Process /Repair Side Scan
08/15	Analysis/Repair	Post Process /Repair Side Scan
08/16	Demonstration	Phase 4 - Side Scan Survey
08/17	Demonstration	Phase 4 - Side Scan Survey
08/18	Pack/Secure	Pack/Secure Hardware for Transp.

Planned versus actual demonstration events.

The demonstration team planned to use the side scan and bathymetric systems to detect and map potential targets on the seafloor in both calibration and demonstration areas and to identify areas of unconsolidated sediments where targets might be buried. These data would guide subsequent sweeps with the

seismic, magnetic and electromagnetic sensors in water depths from 5m to 50m. The airborne hyperspectral imaging system would survey areas with water depths less than 5m. Table 4 outlines the planned activities compared to the actual activities that occurred.

Several events prevented MMTC from conducting the survey as planned. The side scan sonar was the key sensor in the planned survey. Flooding of the sensor during the phase 2 testing, and the inability to repair or replace the side scan until near the end of testing, disrupted the entire demonstration plan. With no side scan data, prospective targets could not be detected.

Further events that prevented an effective search phase were the decision of the magnetometer manufacturer to withdraw from the demonstration, and an unstable baseline reading on the electromagnetic system that caused MMTC to withdraw it.

After locating a replacement side scan system, MMTC was able to gather data near the end of the demonstration. These data were useful, but the demonstration team could not make real time or accurate determinations of the side scan sensor position due to acoustic cross-talk between the ultra-short baseline subsurface positioning system and the side scan sonar. The positioning system interfered acoustically with the side scan return and therefore could not be used. Instead they used layback calculations to compute side scan towfish position. They reported a navigation error, compared to known target positions in the calibration range, of 35 meters with a standard deviation of 20 meters.

Seakeeping considerations dictated that the survey vessel not venture into water shallower than 10 meters. The original MMTC plan had called for side scan and seismic surveying to water depths of 5 meters. The result was that the portion of the demonstration and calibration ranges in water depths less than 10 meters were not surveyed. In addition, a small area near the seaward limit of the range could not be surveyed because 3 to 4 knot tow speeds, required for steerageway of the vessel, prevented the sensor from descending to the proper depth near the deeper boundary of the range (no depressor weight was used with the side scan sonar tow fish). The result was that the actual range area surveyed by the side scan was 3.8 square kilometers rather than the entire 4.6 square kilometers.

The airborne hyperspectral imaging system was unable to detect targets in the water due to low contrast caused by sea surface reflections and scattering within the water. A calibration panel placed on the beach was stolen, restricting processing options.

Additional details on the events referred to above will be provided in the MMTC final report of the demonstration.

Table 4. Planned versus actual demonstration activities.

Planned activities	Actual activities and comments
Phase 1. System assembly and check out. Operate all equipment at MMTC's test site near the Kewalo Basin, Oahu.	The side scan sonar, chirp seismic system, electromagnetic detection system and the AAHIS were operated briefly. The phased array seismic system was assembled and checked out in the Gulf of Mexico. The swath bathymeteric sonar was checked out by the manufacturer. The manufacturer of the Cesium magnetometer withdrew it from the demonstration.
Phase 2. Side scan and bathymetric survey. Conduct simultaneous side scan and bathymeteric survey in all calibration and demonstration areas with water depth greater than 5 m. Identify potential targets and areas of unconsolidated sediments. Planned survey time 2 days. Planned analysis time 2 days.	Side scan sensor flooding prevented its use. Potential targets not identified. Two areas of unconsolidated sediments identified by the swath system, but narrow beam prevented complete bottom survey of calibration and demonstration areas. Survey time 2 days. Analysis and repair time 3 days.
Phase 3. System training in the calibration area. Survey calibration area with magnetic, electro-magnetic, and two seismic systems. Survey 3 days. Analysis 4 days.	Electromagnetic system not used due to problems in establishing stable baseline. Both seismic systems used to survey calibration area. Unable to navigate well enough to assure that targets were within the narrow beams of the seismic systems. Survey time 3 days. Analysis and repair time 5 days.
Phase 4. Survey demonstration area with magnetic, electro-magnetic, and seismic sensors. Focus survey on potential targets identified in phase 2 with side scan sonar. Survey 3 days. Quick look report.	Side scan sonar used to map portions of the demonstration and calibration ranges with water depth greater than 10 meters. Cross talk between the USBL subsurface positioning system and the side scan sensor required shut down of the USBL system. Unable to do real time tracking of the side scan sensor. Eighty-eight objects were detected and reported as ordnance. Survey time 2 days.
Phase 5. AAHIS calibration and demonstration survey. Survey the areas in the calibration demonstration ranges with water depths less than 5 m.	Sea surface reflections and scattering left insufficient contrast for detection of sub-sea targets. Survey time 2 days.

DEMONSTRATION PRELIMINARY SCORING

NFESC completed preliminary scoring in late March, 1996. The scoring is based on MMTC's Interim Report dated 10 March, 1996.

Target Set for Evaluation

As discussed previously, the demonstration team surveyed 3.8 square kilometers of the total 4.6 square kilometers in the demonstration area. There were 145 targets (both inert ordnance and false targets) in the area surveyed. These 145 targets comprised the Baseline Target Set for the preliminary evaluation.

Overall Detection Rate.

The Overall Detection Rate is a measure of the demonstrator's ability to detect all types of targets, regardless of their ability to correctly identify them as ordnance or non-ordnance. Overall Detection Rate (DR_{all}) is calculated as follows:

DR_{all} = Number of Objects Reported within Critical Radius (R_{crit}) of a Baseline Target divided by the Number of Baseline Targets times 100

Where R_{crit} is the distance within which credit is given for a detection.

NFESC stipulated the Critical Radius for the preliminary analysis as 31 meters. The practical application of the Critical Radius involves relocating an object (as for relocating UXO for the purpose of disarming it). No system has been designated as the one to be used for relocation. Therefore, NFESC assumed that a system similar to the one used by the demonstration team would also be used for relocation and estimated navigation errors for that hypothetical system.. Errors are based on 3 standard deviations, that is 99% of reported errors are less than the value listed below. R_{crit} was estimated as follows:

Radial Error Source

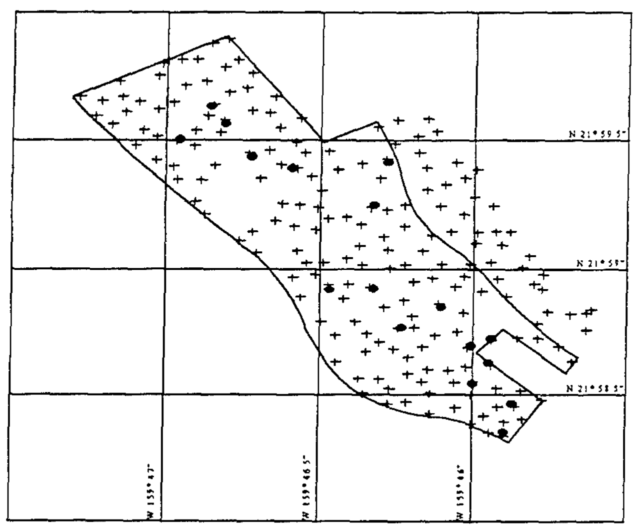
3m	vessel position, using differential global positioning
10m	towfish position relative to vessel, using cable layback technique
18m	target position relative to towfish, assuming towfish crab angle of 10 deg and 100m slant range to target
31m	Total estimated error = R_{crit}

Therefore, with this system, one could go to the reported target location and detect the object 99 out of 100 times.

Objects reported by the demonstration team: 88
Objects within R_{crit} of a Baseline Target: 17
Overall Detection Rate: 12%

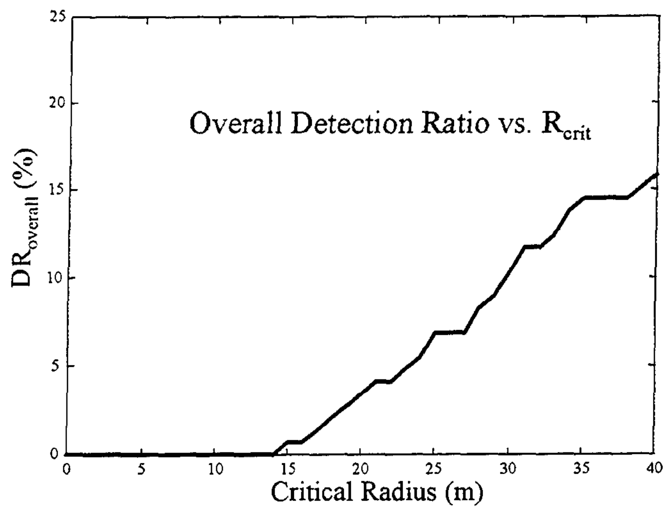
Figure 4 shows the area of the range between the 10 meter and 50 meter contour lines, the installed target positions (+'s), and the positions of the 17 objects (o's) detected within 31 meters of a baseline target.

Figure 4. Target Positions and Object Detections



Other values of R_{crit} are applicable for other systems that might be used for relocation of targets. For example, a typical value of R_{crit} for a diver search is 15m. A range of R_{crit} values and their corresponding Overall Detection Ratios are shown in Figure 5.

Figure 5. Overall Detection Ratio versus Critical Radius



Falsely Detected Targets

Most of the objects detected by the demonstration team were not part of the Baseline Target Set. These 71 Falsely Detected Targets (FDT) could have been actual ordnance, debris or perhaps natural features like outcropping rock or coral. NFESC's plan to investigate these FDT's to confirm their identity could not be done, since the demonstration team was not able to provide locations until several months after the completion of the survey.

DISCUSSION

The need to establish credible test sites designed to evaluate potential UXO mapping and classification technologies, both on land and underwater, is now greater than ever. The range established for the STMC project provided such a site. The design and layout of the range, and the techniques and hardware that were used to install and recover the targets met the requirements of the project. STMC range installation and recovery operations were successfully completed on time and under the budget allocated for the project.

The side scan sonar was the primary sensor for the demonstration. It's failure, combined with the withdrawal of the magnetic and electro-magnetic sensors removed the means for differentiating ordnance from non-ordnance. However, even when it was working, the side scan detected a low percentage of the Baseline Targets. The side scan, especially at the higher frequency, should theoretically detect most of the Baseline Targets. Three possible explanations are:

1) the search pattern used did not enable the sensor to ensonify all targets or,

2) recognition software did not identify target signatures or,
3) Side scan lines were run parallel to the depth contours only, contributing to inability to detect objects that were oriented with their long axis perpendicular to shore.

The subsurface navigation problems experienced undoubtedly contributed to the large errors in the reported position of Baseline Targets detected, but should not have influenced detections.

The seismic systems were reported to perform as expected. However, preliminary indications are that they did not detect any buried targets. These systems, due to their narrow beam width, covered a small percentage of the area in the demonstration range. It is possible that they never ensonified any of the baseline targets.

Another significant impact of the navigation problems experienced by the demonstration team was that Falsely Detected Targets could not be investigated. The inability to investigate detections reported by the demonstration team limited NFESC's capability for independently assessing the causes of the false detections. In general, reliance on the demonstrator's navigation information limits the depth of assessment that can be performed by the scorer.

The time constraints, imposed by the need to recover the Baseline Targets before the high wave season began, removed the margin for error in conducting the demonstration. In the time available the demonstration team was unable to fully recover from the side scan sonar problems that were experienced, or to fully integrate navigation equipment with their side scan or seismic systems. Similarly, there was no time to obtain another magnetometer or solve the shifting baseline problem experienced with the electro-magnetic system.

No significant step in Overall Detection Rate was noted at any value of Critical Radius. This may be an indicator of software recognition and navigation integration problems and is being further investigated by MMTC.

CONCLUSIONS

1. The techniques for installing and recovering the range hardware worked as planned. These were, however, labor and asset intensive operations, and should be undertaken only when permanent range facilities are not available.

2. Since there was no independent range tracking of the user's vessels and sensors, identification of the Falsely Detected Targets must be done with the navigation data supplied by the range user. If these data are not available, or not accurate, it is not possible to identify the Falsely Detected Targets.

3. The question of whether side scan sonar and seismic exploration systems used for mineral exploration are acceptable for detecting underwater UXO can not be confirmed or denied with the data gathered in the demonstration. Despite the extremely low overall detection ratios, the operational problems experienced by the demonstration team prevented a conclusive assessment of the applicability of these technologies.

4. The performance of magnetic and electromagnetic techniques for detecting underwater UXO in the high magnetic background environment could not be evaluated since the demonstration team was not able to operate these sensors on the range.

5. The only attempt to detect Baseline Targets in depths less than 10 meters was with the airborne hyper-spectral imaging system. However, due to various problems that occurred this effort was not successful in detecting any Baseline Targets. Locating UXO in shallow water is important, yet based on the results of the systems demonstrated, it is the most difficult to accomplish.

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ORDNANCE AND EXPLOSIVES COST-EFFECTIVENESS RISK TOOL (OECert)

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ABSTRACT

A mathematical/engineering risk model has been developed by the U.S. Army Corps of Engineers and QuantiTech, Inc. for use in the defining of Ordnance and Explosives (OE) risk at Formerly Used Defense Sites (FUDS). The model uses several factors at a site (density of ordnance, type of ordnance, terrain features, population density, and many others) to determine the risk to public safety at the site. The model uses many of these same factors, as well as other factors to develop rough order of magnitude life cycle costs for the site. The model will allow the Government to develop a prioritized work list for the FUD sites, as well as to perform prioritized work between different sub-sites of a site. The model will also assist the decision maker in performing cost/ benefit tradeoffs. The prioritization list will be used to ensure that the work that will reduce public risk the most for each dollar spent will be performed first. The model can also be used to determine the inherent risk at a site and can be used to determine when a site has been remediated to some previously specified level.

1.0 INTRODUCTION

The cost-effective remediation of sites which have been contaminated by Ordnance and Explosives is an elusive goal. The U.S. Army Engineering and Support Center, Huntsville, in its role as OE Mandatory Center of Expertise and Design Center, has taken on the difficult task of formulating a quantitative risk tool to calculate the amount of risk reduction that can be achieved per dollar spent on OE site remediation. This tool, developed by QuantiTech, Inc. is the OE Cost Effectiveness Risk Tool (OECert). The model facilitates cost planning and aids in the formulation of remediation standards for all OE contaminated sites. The following sections provide a general overview of each of the modules, addressing background, methodology, data requirements, and model output products.

The OECert methodology is built around the exposure of the public to risk and the life cycle cost of the contaminated site through the phases of pre-remediation, remediation and post-remediation. Site assessment must precede any meaningful assessment of cost-effectiveness. The factors which drive cost-effectiveness are summarized in Figure 1. An important characteristic of OECert is the explicit integration of demographics with the characteristics which define the degree of contamination.

OECert prioritizes sites based on risk, cost, or cost-effectiveness ration. Effectiveness is measured by the risk reduction that can be obtained through remediation of a site. As shown in Figure 1, cost and risk reduction are dependent on a large number of variables. Cost for prioritization purposes, is measured in constant year dollars and includes the direct and indirect cost of remediation. The following summary explains how risk and cost are estimated, as well as how the cost-effectiveness ratio is calculated.

2.0 RISK ESTIMATION

A widely accepted definition of risk states that risk is equal to the product of the probability of an event occurring and the consequences of that event. This parallels the estimation approach used in OECert. An event is defined as the exposure by one member of the public to at least one ordnance item. The consequence of this event is defined as the relative hazard associated with the OE located on the site. Hazard subjectively combines both the sensitivity of the ordnance and the consequences of the explosion.

The expected number of exposures to ordnance at a site is a function of the number of people entering the site, the activities they are performing, and the amount, type and visibility of ordnance contamination at the site.

For each activity occurring at a site, the expected number of exposures for a single individual performing that activity is determined based on the area covered by the individual, the OE contamination density, and the surface/subsurface distribution of the OE. Next, the expected number of participants in that activity for the particular site is calculated using the local demographics, activity participation rates and percentages, and the presence/absence of "competing" sites to perform the activity. These values are calculated and summed for all activities occurring in the site, yielding a total expected number of exposures. Risk then is calculated as the product of the expected exposures and the hazard factor for the OE contamination at the site. The fundamental risk equation for dispersed areas and their associated activities is summarized in Figure 2.

The amount of unexploded ordnance (UXO) contamination at a site may be described in terms of density or area and visibility of contamination. If the ordnance is spread over a relative large geographic area (i.e. dispersed sites), density (expressed as the number of UXO items per unit area) is used to describe the extent of ordnance contamination. Intuitively, the higher the density, the higher the risk of exposure. If the ordnance is confined to a relatively well defined area (i.e. localized sites), the two dimensional area containing the ordnance or line of sight surrounding the contaminated area is the measure that describes the extent of contamination. It is assumed that the larger the area the hazard occupies, or the more visible the hazard is, the higher the risk of public exposure.

The type of ordnance contamination at a site may be classified as one of eleven categories. These categories were identified by UXO professionals experienced in the handling and disposal of UXO and are as follows: dispersed UXO; dispersed UXO with special fuzing mechanisms; dispersed UXO with a charge of white phosphorus; dispersed controlled chemical biological or radiological weapons; localized armed UXO; localized unarmed UXO; explosives and materiel; propellants and pyrotechnics; non-controlled chemicals; bulk white phosphorus; localized controlled chemical, biological, and radiological weapons. Each of these ordnance categories has two relative hazard factors associated with it. These relative values describe the consequence of an ordnance item detonating and the sensitivity to detonation of the ordnance in each hazard classification.

3.0 COST ESTIMATION

A site's life-cycle is made up of three parts: pre-remediation, remediation and post-remediation. Cost estimates for these phases and the sum of these estimates provides a total site life cycle cost estimate.

Pre-remediation is the time period beginning when the site is identified and placed on the list of sites to be prioritized, and ending when remediation begins. Costs associated with this phase include any personnel, equipment, and material costs incurred during activities, such as feasibility studies, engineering evaluations, and site planning that take place to facilitate the site being prioritized and/or remediated.

Remediation is the time period when the physical site clean-up occurs. Cost associated with this phase include all personnel, equipment and material costs directly or indirectly related to the actual clean-up of ordnance contamination at the site. Remediation is expected to be the most cost intensive phase of the site life-cycle.

Post-remediation is the time period beginning when the site remediation effort ends and ending at the end of the analysis period. The total site life-cycle is assumed to be 30 years. Post-remediation under this assumption would be 30 years minus the number of years required for pre-remediation and remediation. Costs associated with this phase include any personnel, equipment, and material costs relating to activities required to limit public entry to the site (i.e. fence maintenance, guards, etc.). If the site is completely turned over for public use after remediation, there will be no post remediation cost associated with the site.

The cost module uses a combination of all four widely accepted cost-estimating methods depending on the data available. This combination of methods takes place within a framework of a "bottoms-up" work breakdown structure. The four methods are p arametrics, engineering (bottoms-up), analogies, and expert opinion. Parametric estimates are those that apply quantitative methods to arrive at estimating relationships between cost elements. The expected evolution of OECert cost methodology is from parametric, through analogous, to bottoms-up. For example, by gathering actual contract data and applying regression analysis, a percentage can be applied to remediation clearance time to arrive at quality assurance time. The engineering, or bottoms-up approach, estimates at a piece part level and requires a great deal of experience in the activities being estimated. Analogies are costs that are estimated using actual costs from programs based on similarities that characterize the programs. Often, with analogies, complexity factors are used to adjust the cost upward or downward to account for the differences between technical considerations. Expert opinion estimates are judgments expressed by those with education and experience in the particular area being estimated.

Currently, the cost module's estimates are built on actual data collected at Mission Trails/Tierrasanta and Raritan sites and data from the OE-CWM Generic Cost Estimate. For prioritization and cost planning purposes, a database is

being developed to supplement and enhance the previously gathered data. This database will provide consistency for studies, analyses, and budget and planning exercises and result in the reduction of cost analysis subjectivity.

Cost data is available to build the database. The data requirements include actual contract cost data, interviewing remediation participants and experts, analysis of data, and making provisions for cost feedback over time.

The model output for the cost module consists of a series of reports and briefing charts that summarize life-cycle cost. These reports are arranged by pre-remediation, remediation, post-remediation, and cost of no remediation. Reports are available to meet the various needs of the budgeting exercises, trade studies, and various other analyses. Within three life cycle elements, the work breakdown structure is employed to show costs at the lower levels. The cost module also shows costs either held constant or adjusted for inflation (escalated) and calculates both present and future values for the purpose of economic analyses dealing with the time value of money and alternate investment strategies.

4.0 COST-EFFECTIVENESS MEASURE

The prioritization of sites is based on a calculated cost-effectiveness ratio for each site. The cost-effectiveness measure compares delta risk to delta cost for each site. Delta risk is the difference between the estimated level of risk associated with the site before remediation occurs and the risk level established as the remediation standard. Delta cost is the difference between the life-cycle cost including remediation and the life cycle cost with no remediation phase included. The ratio resulting from these calculations gives the amount of expected risk reduction per dollar spent at the site under analysis.

5.0 DATA REQUIREMENTS

The data required to execute OECert can be placed into four broad categories: demographic data, parametric data, expert opinion data, and site assessment data. Data categories and sources gathered thus far are presented in tabular form. Data values that currently are nominal have potential data sources listed.

Demographic data includes, population totals, activity participation rates, gross and new construction building permit totals, average construction site sizes, surveying activity totals, and state and national park totals. These data values, with the exception of construction site size, are used in the calculation of the potential number of entrants to a contaminated site. Construction site size is used in the calculation of subsurface risk area.

Population totals are collected by count or city and are broken down into nine age categories. Activity participation rate data is broken down into the same nine age categories and is based on national participation statistics. Building permits are collected at the city and county level. Surveying activity is a nominal value based on local information and uses the number of "new" building permits issued. "New" construction is assumed to be all building not related to renovation, alteration, or addition. The number of state and national parks is collected on a state by state basis, but is implemented at the regional level. Table 1 summarizes the demographic data sources.

The parametric data set consists of the parameters needed to describe an individual's participation in identified activities. These parameters are: subsurface area covered by an individual, path width of an individual, an individual's activity participation time, an individual's velocity while performing an activity, and velocity degradation resulting rom the terrain conditions. Not all parameters are applicable to all activities. The values are used in the calculation of the area an individual covers while at a site. Table 2 presents the current parametric data requirements, sources for "hard" numbers, and proposed sources for nominal values.

Expert opinion data requirements consist of hazard factors elicited from UXO/EOD professionals through application of the Analytic Hierarchy Process (AHP) developed by T.L. Saaty of the University of Pittsburgh. THE AHP is an analytic technique that requires subject matter experts to compare the importance, in this case, sensitivity and consequence, of one ordnance item to another on a 1 to 9 scale of absolute numbers, 1 indicating equal importance and 9 indicating absolute superiority of one item to the other. A team of UXO safety professionals from the Corps of Engineers, Huntsville Division, participated in an AHP session and their input became the basis for the hazard classification. The hazard factor is the product of the sensitivity factor times the consequence factor. These factors have been adjusted to a scale from 1 to 100 for ease of application and presentation purposes. Table 3 lists the eleven hazard classifications along with their respective hazard factor values.

Table 1. Demographic Data Sources

Data Required	Source
Population Totals	United States Census Bureau CD ROM
Activity Participation	American Sports Data Rates Inc. American Sports Analysis 1992 Summary Report
Building Permits	United States Census Bureau Construction Statistics 1988-1992
Surveying Activities	Local data based on number of new building permits issued
Average Construction Size	Nominal value based on estimates of local Realtor
State and National Park Totals	The Outdoor Atlas and Recreation Guide 1992

Table 2. Parametric Data Sources

Data Required	Proposed Source
Subsurface Area	Outdoor Recreational guides
Path Width	Ergonomic studies
Participation tim	Marketing Surveys
Velocity	Army Field Manual 21-18
Velocity Degradation	Army Field Manual 21-18

Table 3. UXO Hazard Factors

UXO Type Dispersed	Sensitivity Factor	Consequences Factor	Product Factor	Hazard
UXO	126	80	10,080	29
UXO Light Motion	327	80	26,160	76
UXO White Phos	126	36	4,536	13
Controlled Chem, Biological or Rad	126	273	34,398	100
UXO Armed	126	80	10,080	29
UXO Unarmed	16	80	1,280	4
Explosives and Material	24	36	864	3
Propellants and Pyrotechnics	43	18	774	3
Non-Controlled Ch	22	15	330	1
White Phosporus	44	20	880	3
Controlled Chem, Biological or Rad	22	281	6,182	18

6.0 MODEL EXECUTION

To run OECert, several key pieces of information must be obtained. The information needed for a dispersed site include the following items: hazard type; degree of slope; vegetation type; presence of slippery ground cover; percentage of UXO on the surface; sector UXO and total item density; weighted average of UXO weights; soil type; sector acreage; presence of bees, snakes, and poisonous foliage; presence of archaeological activity; presence of environmentally sensitive plants and wildlife; fencing required; number of guards needed and knowledge of which activities occur at the site.

For a localized site the following information is needed: hazard type, degree of slope, vegetation type, presence of slippery ground cover, area of hazard, maximum line of sight distance surrounding the hazard, excavation volume, area to be reconstituted, environmental factors, sifter requirement, fencing required, number of guards needed, knowledge of which activities occur at the site, OE removal volume, area to be prepared for clearance, and area of original site.

The model outputs from OECert will consist of a list sites prioritized by risk, cost, or cost-effectiveness ratio. The prioritized list may consist of any subset of the sites present in the database at the time of analysis. Additionally, detail risk estimates are provided at a "per activity" level, as well as life cycle cost estimates.

7.0 FUTURE USAGE

In the future, OECert will be expanded to handle many of the challenging issues pertaining to ordnance remediation. In addition to site prioritization based on cost-effectiveness, the following applications will be available.

7.1 Defacto Risk Standard Density

Defacto risk standards are being developed to determine when a site has been cleaned to an acceptable level. To develop these standards, the post-remediation risk is being measured at sites that have been cleaned to an acceptable level for their current land usage. These defacto standards will be based on the following definitions of risk: (1) the probability of exposure to ordnance for one person during a single site visit, and (2) the expected number of exposures to the surrounding population annually. In the future, OECert will accept a risk standard as input and compute the corresponding post-remediation ordnance density that must be achieved in order to meet the defacto risk standard.

7.2 Remediation Planning Tool

A remediation planning tool is being developed so that the project managers of formerly used defense sites may assess site remediation alternatives. These alternatives are base on : (1) a specified level of work performed, (2) a specified cost of remediation or (3) a specified residual risk. The tool is intended to assist im making level of remediation versus cost of remediation decisions.

A specified level of work is defined to be the clearance of UXO to a specified depth assuming some achieved sweep efficiency. Sweep efficiency is the portion of anomalies detected and removed in the clearance action. A specified cost is defined to be the remediation cost associated with clearance of UXO to some combination of level of work (clearance depth) and sweep efficiency which will result in the specified dollars. A specified risk is defined to be the probability of exposure (for an individual at a FUDS) associated with clearance of UXO to some combination of level of work (clearance depth) and sweep efficiency which will result in the specified residual risk.

7.3 Summary

The quantification of OE contamination is a necessary and prudent part of the management of sites which have been used by our armed forces. The quantification is necessary to communicate with the public and to plan remediation activities. A continued evolution of the OECert methodology will serve as a foundation for difficult future decisions concerning the allocation of scarce resources to very sensitive issues of great public concern.

ORDNANCE AND EXPLOSIVES (OE) PROGRAM GEOGRAPHIC INFORMATION SYSTEM (GIS) AND KNOWLEDGE BASE (KB)

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ABSTRACT.. To facilitate the detection and removal of buried munitions, the U.S. Army Engineering and Support Center, Huntsville adapted the Geographic Information System (GIS), thereby developing a standard methodology for OE use. As a central repository for site information, OE-GIS is used (1) to manage the OE program and individual projects, (2) to assemble the data from site investigations so that the need for further investigation can be determined, (3) to discriminate ordnance from background anomalies, (4) to administer the removal of ordnance items, and (5) to digitally store the data for the administrative record. Using off-the-shelf software and a personal computer, OE-GIS collects, integrates, archives, and analyzes data from OE site investigations. An important part of OE-GIS analysis is performed by the OE Knowledge Base (KB) module. OE-KB is an ever-growing data base of measurements of underground activity taken by non-intrusive instruments, such as metal detectors and conductivity meters. To get better measurements, instruments are constantly being evaluated and modified. By analyzing the measurements of underground activity, the OE-KB module discriminates ordnance anomalies from background noise, measures anomaly size, predicts the most probable anomaly locations for investigation, and develops a data base of ordnance characteristics that can eventually be used to "fingerprint" an ordnance item. The analysis method used by OE-KB is artificial-intelligence neural network, which evaluates the magnitude of each point in the data while also establishing relationships between all data points. The main objective of OE-KB predictions is to reduce the amount of digging. GIS techniques have been developed, tested, and applied at several OE sites with review by an independent peer group.

INTRODUCTION

Purpose. Over recent years, the U.S. Army Engineering and Support Center, Huntsville adapted the Intergraph MGE Geographic Information System (GIS) for use with ordnance detection. This paper explains how Ordnance and Explosives (OE) GIS facilitates the detection of buried ordnance through the OE-GIS Knowledge Base (KB), a data base of information from non-intrusive detection instruments, such as magnetometers and conductivity meters.

Scope. This paper covers three major areas: (1) a description of the development of OE-GIS applications and how they relate to OE-GIS, (2) a description of the geophysical tools used to gather data for OE-KB, and (3) a description of the technology behind OE-KB analysis.

Background. For decades the U.S. Armed Forces have used land and water areas for the production, testing, training and disposal of OE. An unfortunate by-product of this use is a potential hazard to the public: unexploded ordnance (UXO). In the recent past, several geophysical data analysis techniques have been developed and used for UXO detection. However, very few significant improvements in this area had been achieved. Without standard operating procedures relating specifically to geophysical data analysis at OE sites, several problems arose: (1) a need for standardized techniques and results, (2) a difficulty in implementing quality assurance/quality control procedures, and (3) a reluctance on the part of contractors to use advanced geophysical techniques. To confront those difficulties, the U.S. Army Engineering

and Support Center, Huntsville began developing a set of detection and classification tools to improve and standardize OE operation. Those tools are all centered around a full function Geographical Information System (GIS) that integrates typical OE operations.

THE DEVELOPMENT OF OE-GIS APPLICATIONS AND KNOWLEDGE BASE

Project History. U.S. Army Engineering and Support Center, Huntsville, got started in ordnance cleanup in the late 1980's. In April 1990, the Center was designated the Mandatory Center of Expertise (MCX) for the OE Program because of its experience in ordnance investigations. The MCX's mission is to eliminate or reduce the imminent danger to the public posed by abandoned OE at current or formerly used defense sites through education, policy, performance, and quality assurance. As the MCX, Huntsville Center is responsible for OE activities supporting the Defense Environmental Restoration Program for Formerly Used Defense Sites, the Installation Restoration Program, the Base Realignment and Closure Program, and the Service for Others Program. With over 2,000 inventoried sites, those programs normally administer 60 to 80 active projects at any given time. Over the years, as removal projects proliferated, Huntsville sought better methods of ordnance detection. OE-GIS, along with the OE-KB, is a result of that search.

Project Description. Huntsville Center led the effort to standardize GIS and used that technology to facilitate ordnance detection on several projects. As a central repository for site information, OE-GIS is used (1) to manage the OE program and individual projects, (2) to assemble the data from site investigations so that the need for further investigation can be determined, (3) to discriminate ordnance from background anomalies, (4) to administer the removal of ordnance items, and (5) to digitally store the data for the administrative record.

Huntsville Center applies the OE-GIS standard to projects that (1) are from different geographic locations, (2) have differing environmental characteristics and widely varying types of ordnance and dispersion patterns, and (3) may use various geophysical investigative instruments and technologies for subsurface investigations. Those projects include Fort Monroe, Camp Simms, Camp Croft, Duck, Motlow, Nebraska Ordnance Plant, Redstone Arsenal, and Pueblo Army Depot. The data collected from project site investigations is incorporated into the OE-GIS data base. Such data include historical, survey and mapping, remote sensing, and non-intrusive subsurface geophysical information. Drawing on its data base, OE-GIS associates the data to their coincident geographical locations and to the relational data base for non-spatial data. For example, a historical aerial photo of a site could be registered with its state grid plane coordinates, facilitating accurate mapping of grids for site investigations.

Through its Knowledge Base module, OE-GIS can distinguish anomalies (that is, possible items of ordnance) from the background noise detected by instruments during a site sweep. To perform anomaly discrimination, the OE-GIS environment compiles the field data and provides the framework for OE-KB analysis techniques. That framework also provides the mechanism to apply lessons learned from one project to multiple sites. Once the innovative techniques have been proven and standardized, they will then become part of OE-GIS and KB as applied in the field.

GIS Applications. To facilitate site investigations, Huntsville Center developed a standard methodology for GIS off-the-shelf PC software. That OE-GIS standard enables geologists, engineers, and technicians to apply GIS tools consistently and in concert with the Tri-Service GIS Spatial Data Standard (TSSDS). Used to its fullest, OE-GIS becomes the hub of a site investigation—integrating, analyzing, and archiving all site data.

By comparing all data to a common geographical reference and then predicting the most probable ordnance locations, OE-GIS is used to determine site areas needing further investigation. Equally important, however, OE-GIS can provide administrative record justification for "no further action" recommendations. For example, site areas that have had earthwork changes, such as large cuts or fills, have a low probability of near-surface ordnance. Those areas would not be candidates for detailed investigation.

To make its predictions, OE-GIS draws on a data base of items found in previous investigations as well as other information that will assist in locating and discriminating ordnance. Also included in the OE-GIS data base are the property owners within the project area. They are needed for tracking right-of-entry, evacuation notification, and other project requirements. Through various tools, OE-GIS can provide three dimensional analysis, historical comparison of mapping, remote-sensing data and aerial photography images, image processing, geophysical mapping analysis, and statistical probability analysis.

Another use of OE-GIS comes after the areas of concern are determined. Then OE-GIS can be used to manage the work flow and provide maps, perform geophysical analysis and discrimination of anomalies, facilitate data

base queries and storage, and provide the principal medium for the administrative record.

The basic OE-GIS standard is the starting point, but each project is unique and requires the use of a different collection of GIS tools that provides the best, most economical fit for the project requirements.

Project Work Flow. To collect planimetric data such as roads, buildings, utilities, woods lines, and drainage pattern, the project sites are first surveyed by ground and/or photogrametric techniques. Where required, a three dimensional model data (generally represented by contours) is generated. The survey data are then captured as computer aided-design and drafting (CADD) files. Those digital design files provide the basic data for the registration and input of historical maps and current and historical aerial photographs. The aerial photographs from the survey are processed into digital orthophotos or scanned and digitally rectified. Any other information that will assist in determining and isolating geophysical anomalies is also captured and integrated in the OE-GIS data base—archival data such as historical maps, drawings, photos, and site layouts and items such as property ownership, utilities, and tax assessment records.

Next, the data are linked, or associated, to a common positional reference to support project investigations. For example, to provide a means of accurately locating site positions over time, historical maps and aerial photos are converted to the current state grid plane coordinates system and associated with recent mapping efforts. OE-GIS then uses the associated data to provide evidence of probable ordnance contamination. Such evidence includes processed images of impact and disposal areas and spatial analysis of past land use. Once areas of concern are identified, non-intrusive geophysical survey techniques are used to identify anomalies in preparation for OE-KB analysis. Depending upon the techniques used, OE-GIS then models the data and provides the framework for OE-KB to discriminate the geophysical anomalies from background signals. After anomaly selection by KB, OE-GIS is used to manage the excavation performed by UXO specialists and to incorporate and store the results for the project and for future OE-KB use.

OE-KB. OE-KB is a data base of various site specific characteristics, including measurements collected with geophysical instruments during various site investigations. As more sites are investigated and more measurements are taken, data are added to the OE-KB.

Such data can be analyzed by the OE-KB module. The specific type of data manipulation depends upon the geophysical instrument or type of sensor employed. To date, geophysical data from the Geonics EM-61 conductivity meter and the TM-4 magnetometer have provided the basic input for analysis. Data analysis includes arithmetic manipulations, statistical ratios, Fourier transforms, matrices, and Intergraph GIS software routines. Through the OE-KB module, anomaly characteristics can be compared to known electronic signatures, processed numerical signatures, and interpreted image signatures to further streamline the OE investigation.

Analysis of OE-KB data can help the OE community reach several objectives that would facilitate ordnance detection. One objective is to use OE-KB data to establish a profile, or "fingerprint," for specific ordnance items. Those fingerprints could then be used during future projects to evaluate and identify anomalies. Another objective is to archive the occurrence of OE and related site-specific conditions for each project. A third objective is to provide quantitative analyses of characteristics collected by non-intrusive geophysical surveys, such as mass and depth.

To attain those objectives, OE-KB must be continuously updated with information from new projects and new technologies. The initial OE-KB (called KB-1) was created through the Fort Monroe site investigation. That investigation used manual methods to measure the shape characteristics and to input the data. The latest version of OE-KB (KB-2) uses artificial-intelligence, neural-network techniques to assist in anomaly identification. Intended for use by various customers, KB-2 is a tested, documented product with an on screen push button graphical user interface. The Center has committed to develop and apply those techniques.

GIS Hardware and Software Platform. GIS software runs on a personal computer (PC) with Intel Pentium processor, Windows NT version 3.51 operating system, and a minimum of 32 megabytes of random access memory (RAM). Additional capability may be desired depending on the project size and other needs. For example, a more powerful workstation would mean faster processing and accessing of GIS data but is not required to run the software. Huntsville Center uses Intergraph TD-4 Intel dual Pentium GIS machines with 96 megabytes of RAM.

All development and project data is exclusively targeted for PCs running the Windows NT 3.51 operating system, MicroStation CADD engine, Intergraph Modular GIS Environment (MGE) 6.0 software, and Oracle relational data base. See the UXO Forum exhibit or contact the

authors for specific software requirements and descriptions.

Internet Data Transfer. With all site information archived in the GIS data base, Huntsville Center uses the Internet to transfer and share data such as developmental and fielded GIS data, design drawings, survey data, relational data bases, and related generated data.

GEOPHYSICAL TOOLS AND TECHNIQUES USED TO GATHER DATA FOR THE OE-KB

Because geophysical measurements taken with non-intrusive detection instruments provide the basis of OE-KB analyses, the accuracy of OE-KB predictions depends, in part, on the type and quality of data gathered. That data include ground-truth parameters that describe the location, size, depth, mass, and orientation of a subsurface object; the soil conditions surrounding an object; and the geophysical readings that make up an object's signature. One objective is to accumulate a vast store of geophysical data so that OE-KB will reach one of its primary goals: an identifying "fingerprint" for every type of ordnance item.

Evolution of Ordnance Detection Tools. The diverse nature of ordnance sites, the long functional life of ordnance, and its persistence as a safety hazard has led to the examination of numerous techniques to locate ordnance and explosives, particularly where it has remained as a hazard to human health. Because of the focused application of locating and disposing of ordnance, experience has remained confined to Department of Defense and law enforcement agencies.

Military organizations first began fielding devices designed to locate buried munitions, particularly ferrous landmines, shortly before World War II. The first mine detectors located ordnance by measuring a fluctuation in the earth's magnetic field at the site of the ordnance item. As a counter-measure, manufacturers began constructing mines containing little or no ferrous metal. Today, the best military mine/ordnance detectors generally use two technologies, magnetometer or conductivity, depending on whether ferrous or non-ferrous objects are being sought or on specific site conditions.

Independent of the military's sponsorship of mine/ ordnance detectors, the mineral exploration industry placed demands on geophysicists, geologists, and other exploration personnel to locate a wide variety of ore types. Development of powerful computers greatly enhanced the ability to interpret, analyze, and fuse the very large data sets collected by current sensors and analytical techniques. While the use of magnetometers and metal detectors continued in the explosive ordnance disposal (EOD) community, capabilities of these instruments were greatly improved within the mining and environmental community through the use of complementary sensors, analytical techniques, and improved geophysical techniques.

Magnetometers. Magnetometers provide data about subsurface objects by reading the disturbances in the magnetic field surrounding the object. To obtain that data, several types of magnetometers are available. Each type has its advantages and drawbacks. Since any one instrument is not suitable for every environment, the use of multiple instruments can help provide comprehensive data.

Fluxgate magnetometers have long been a standard tool of EOD teams. Fluxgate magnetometers are best for rapid sweeping on foot; they are light weight, relatively precise, and locate anomalies at two coordinates. Military and many other magnetometers provide an analog output, which is awkward to enter into OE-KB; geophysical instruments giving digital outputs when sensing metals are better suited for OE-KB. Proton precession magnetometers are relatively light weight, somewhat more expensive that other types, and locate anomalies precisely at two coordinates; however, they acquire anomalies more slowly than fluxgate or cesium vapor magnetometers. Cesium vapor magnetometers, on the other hand, provide greater precision and are faster than proton precession magnetometers but are slower than fluxgate magnetometers. They are also the most expensive type. Finally, other types of magnetometers such as SQUIDs or fiber optic magnetometers are very expensive but offer significant potential for improvement of magnetometer technology in specific situations.

To gather data with a typical magnetometer, workers sweep the instrument across a 5-foot-wide path as they walk forward. To enhance data collection and area coverage magnetometer sensors can also be linked together and incorporated in an all-terrain vehicle system.

Conductivity Meters. Another tool used extensively by OE teams is the conductivity meter. The main advantage of conductivity meters is that they are useful in detecting non-ferrous ordnance.

There are basically two types of conductivity meters, a frequency domain and a time domain conductivity meter. The frequency domain conductivity meter has been used as a primary geophysical tool on some projects. While it

is effective on some geophysical surveys, it generally is not as effective for OE surveys as the time domain conductivity meter. Time domain conductivity meters have provided the greatest input into OE-KB to date. This instrument locates metals nonintrusively by inducing a current into the ground and observing its decay with time. This instrument may be designed to see objects of a specific size and overlook objects outside of the designed range.

Current off-the-shelf time domain conductivity meters can be depended upon to see ordnance items to a depth of approximately 4 feet while ignoring metallic items of small mass, such as nails and small fragments. With proper post processing, it is common to see geophysical anomalies beyond 5 feet. The accuracy to which an individual anomaly can be located is approximately +/- 2 feet. Lanes with 5-foot spacing are usually surveyed although different spacing may be chosen.

Other instruments. Huntsville Center has made provisions for OE-KB to accept data from other instruments as their capabilities are proven. The Center has been evaluating the ability of a neodymium yttrium-lithium-fluoride (Nd:YLF) laser to find ordnance items from a helicopter or other airborne platform. By looking at the surface texture of the ground, that laser is able to distinguish manmade objects, both plastic and metallic. Huntsville Center, in cooperation with the Navy's Coastal Systems Station, is also evaluating the potential of using the blue-green laser to locate near-shore underwater ordnance. Finally, synthetic aperture ground penetrating radar is being employed at a site to evaluate the possibility of rapidly locating and determining concentrations of ordnance in an area of dense vegetation and moderate relief.

KNOWLEDGE BASE NEURAL NETWORK

As a module of GIS, OE-KB was developed to help determine OE target, or anomaly, characteristics. OE target characteristics include mass and depth. Such characteristics can be determined through the two main OE-KB functional components: (1) a data base of known target characteristics and (2) a suite of analysis software tools.

Signal/Target Data Base. The data base component of the OE-KB is a diverse collection of known "signatures" from excavated ordnance and non-ordnance items. The data base contains ground-truth parameters describing an object's location, size, depth, mass, orientation, and soil conditions. Additionally, each record in the data base contains the sensor data used to detect the target; that geophysical data is referred to as the target signature.

The software accessing the data base has a push button graphical user interface containing several functional levels (Figure 1). The first level enables the user to load a data base of target signatures and associated ground truth parameters. Data base searches can then be performed to evaluate the range of signal characteristics for a given target type, environment, mass, or depth, for example. The data base is available either as a local MicroSoft Access or remote Oracle data set.

The user of the OE-KB can query the signature data base and scroll through the query results to examine target characteristics and review the geophysical data profiles. The user can load a data set of detections containing suspected targets and overlay them on a data base of known signals to visually define matching targets (Figure 2).

Besides offering data review, the software can automatically detect anomalies from raw data. Detected anomalies are configured into a file in the standard OE-KB data base format, and subsequently presented to the operator for visual inspection.

Current Analysis Techniques. There are several analytical methods applicable to the problem of ordnance characterization and discrimination. The first and most common uses a deterministic approach where a formula representing the physical system is created. One or several values are manually or automatically extracted from the signal and are run through the formula. The result is a target characteristic, such as mass or depth. The OE-KB program is well suited to automatically implement this type of analysis.

Another analysis approach is a stochastic, or measurement-based system. The known/unknown anomaly comparison function of the signature data base is a simple version of stochastic analysis. Users of the system will quickly recognize its limitations, including the inexact definition of the signal characteristics indicating that an anomaly is an actual target, and the definition of an acceptable degree of variance between target and signature signifying a match. Furthermore, because this approach depends on subjective visual verification of the target or signature data, stochastic analysis is not considered reliable enough for accurate anomaly discrimination.

Neural Network Technique. One way to reduce operator subjectivity and standardize the process of target selection and classification is to use the computer as the moderator. The OE-KB implements a type of moderator called a neural network. "Neural network" is a term describing a broad category of analytical tools based on

the way brain neurons receive, process, store, and communicate knowledge. Neural networks are successfully used to solve problems that typically defy traditional analytical methods. They are non-linear procedures which produce answers based entirely on empirical evidence, or in human terms, through experience.

The fundamental approach to target classification with the OE-KB is to amass a comprehensive data base of target signatures and associated ground truth and to develop neural network classification tools for standardized operator use. The OE-KB does not remove the operator from the process, but rather provides the operator with modern, tested classification tools to implement a standard operating procedure to detect, locate, and identify ordnance. Skilled and experienced computer operators are still required to execute successful ordnance remediation operations. With OE-KB, however, results will not be based on the talents of a particular operator, but will instead be based on the cumulative knowledge of all operations carried out under this approach.

As more operations are executed under OE-KB, the base of knowledge will increase. Consequently, target classifications will become more accurate, a factor that will lead to more efficient target removal, better use of remediation resources, fewer false alarms, and lower costs.

Application of the Neural Network. The near-surface target classification problem is one in which a neural network solution is a natural choice. Generally, a large number of non-linear variables influence the magnitude and morphology of a geophysical signal representing a shallow subsurface conductive object, such as an ordnance item. The geophysical signature of a target of a given mass and depth is influenced by several related factors, including, but not limited to, soil conditions, other nearby targets, target morphology, target degradation condition, instrument/target spatial configuration, and instrument operating conditions. Those factors make the ordnance signature predictions based on simple analytical functions highly unreliable.

The analytical modeling approach to ordnance signature matching (such as point dipole modes for magnetometer data) requires the simplification of a complex problem in order to accommodate existing simplified mathematical models. A small number of variables are determined under simplifying assumptions using these models, frequently ignoring or grossly underestimating the complicating effects of the overall system.

For example, with conductivity data gathered using the pulsed induction technique, one analytical model relies on only the peak data values in the target signature as input to the classification formula. Tables 1 and 2 show data collected using a dual-coil pulsed induction sensor (Geonics EM61). The three excavated items in the table have the same mass and depth, yet the peak values are very different. Table 2 shows three different items with nearly identical peak values. An analytical result based on the maximum Coil 2 value would incorrectly assign the first three different masses and the second three the same mass. Furthermore, relying on peak values limits accuracy, since values may vary for the same object. The variation in the observed peak value of a target could be the result of physical factors such as material composition variation, soil effects, and object orientation. Additionally, target signature variation can result from differences in the relative position of the instrument with respect to the target.

Table 1

Anomaly ID	Weight (lb)	Depth (in)	Coil 2 Peak (mV)	Coil 1 Coil 2 Ratio
1	10	6	117	1.12
2	10	6	76	1.05
3	10	6	37	1.37

Table 2

Anomaly ID	Weight (lb)	Depth (in)	Coil 2 Peak (mV)	Coil 1 Coil 2 Ratio
4	5	6	24.1	1.19
5	0.3	2	24.3	1.05
6	12	12	24.6	1.07

Although they have drawbacks, simplified analytical models have been used because they can be readily implemented on available inexpensive computers. More comprehensive, sophisticated, and accurate analytical models may be available for routine use in the future, but are not generally available today.

A neural network approach, on the other hand, overcomes many of the disadvantages of simplified analytical methods. A neural network learns the significance of each point in the target data rather than relying on peak data values. A neural network not only assigns a significance (or weight) to the magnitude of each point in the data, but also identifies and defines weights to establish relationships between all data points.

Figure 3 shows the three Coil 2 line signals representing the targets in Table 2. Note the differences in the morphology of the signals. The neural network can exploit those different morphologies to produce different results. The network solves the problem of peak values by simply "remembering" that each of the three signals can represent a target of the same mass.

Neural Network Technology. The neural network in the OE-KB is a multiple-layer feedforward network (MLFN). The version implemented (Masters, 1994) uses a set of sophisticated techniques for establishing and implementing neural networks. A training process is required to build a neural network. During that training procedure, a mathematical relationship between input data and known results (ground truth) is established. After the system is trained, data from unknown targets are processed by the neural network to estimate target depth and mass.

To train the neural network, the MLFN uses a hybrid of simulated annealing and conjugate gradient optimization as the primary training algorithm. The network is operated in the complex domain and allows for the simultaneous input of multiple channels of data (Coil 1 and Coil 2, for example). As currently implemented, the neural network does not accept raw signal data and must be normalized to fit the network's optimal operating conditions. There is an internal algorithm within OE-KB to perform that operation.

The input to the network is a modally adjusted, peak-centered, symmetrically averaged, normalized, differenced, complex domain signal. The output is a normalized complex value where the real part is devolved to a mass value and the imaginary part is the depth value. As indicated, the architecture of the network is multiple layer feedforward with back-propagating errors in the training phase. Multiple layer refers to the existence of multiple layers of neurons. These neurons (more specifically the weights connecting them) give the network the ability to generalize trends or patterns through an associative memory function.

In qualitative terms, during the training phase, each input neuron competes for the opportunity of influencing a limited number of hidden neurons with their importance. Eventually the network, through back propagating the error in its predictions, will diminish the importance of extraneous input neurons by a downward adjustment of the weights of their connections to the layers in the network. Similarly, the network adjusts upward the weights of input neurons that it deems are significant. This function acts a type of data sieve where many points are reduced to fewer significant ones.

The hidden layers are also connected to the output neurons by weights. The neurons serve as organizational memory. They cannot be ranked in importance back to any single input neuron because every input neuron is connected to every hidden neuron within the network. The output weights provide to the network the ability to generalize. As a rule, a network that has too few hidden neurons will over-generalize, like sorting too many classes of an object into too few categories. The results will not properly reflect the true complexity of the problem and the answers will be wrong. A network with too many hidden neurons has too many compartments to store information in. The result is a network without a representative curve, or virtual function, to apply to input signals. In such cases, a target signal that does not exactly match a training example can end up being classified or mapped anywhere in the output spectrum.

For a neural network to successfully solve the OE target classification problem, it must be able to generalize a logical system. Clearly, there exists a geophysical relationship between the recorded signal and the true target characteristics. However, a problem exists in separating other influencing factors from those modeled with simplified analytical equations. Because of the range, significance, and pervasive nature of environmental factors, every signal is to some degree unique. If a neural network required a discrete and identical signature in its memory to correctly classify each unknown target case, then the application of this technology would be ineffectual. However, a well functioning neural network will learn the underlying complex, non-linear system whereby a unique input signal will be mapped onto a continuous output curve. This trait is called generalization.

Neural Network Example. The results of the OE-KB neural network is provided here for reference. The data

used in this example comes from the Geonics EM61 pulsed induction sensor deployed at Camp Simms, Washington, DC, in 1994. During the beginning of this operation several targets were detected, relocated, and excavated to provide ground truth for the OE-KB. That data was used during the training process where the neuron weights were established for the network. Once developed, unknown detections were classified using the weights derived from the ground truth. The results for estimated target mass are shown in Figure 4 where the estimated target weights are plotted against the true weights. Bounding lines are provided to indicate estimate errors in excess of 5 pounds. Thirty-six of 39 target mass estimates fell within this error threshold.

The neural network results for estimated target depth are shown in Figure 5. Six-inch error bounding lines are provided for reference. Thirty-five of 39 target depth estimates were within one-half foot of the true depth, and only one target depth was estimated with an error in excess of one foot.

Testing and Review. During development of OE-KB techniques, Huntsville Center implemented field tests and peer reviews to verify product effectiveness. Field tests were structured to train the OE-KB to predict the occurrence of ordnance and then compare the predicted results to conventional "mag and flag" techniques with the 100% removal results. A peer review group performed an objective review of OE-KB techniques and application during development. Because review and testing have been integral to OE-KB development, they have guided the course to the current product.

KB Maintenance and Enhancement. Currently, OE-KB holds data from selected projects. As GIS is fielded, however, Huntsville Center will add geophysical data from all previous and new ordnance projects, thereby (1) increasing the accuracy of OE-KB predictions, (2) building a comprehensive analytical base, and (3) ensuring the continual development and documentation of OE-KB. Huntsville will also continue to test and incorporate other geophysical instruments and techniques that can improve OE discrimination. Huntsville will evaluate fusing data from various instrument combinations and merging GIS, spatial, or modeling data.

Two KB-2 products will always be active: KB-2 Field and KB-2 Development. KB-2 Field will support only proven technology and techniques, while KB-2 Development will incorporate and test new technology. The two must work together to support each other. When new technology is proven, KB-2 Field will be upgraded; when new geophysical measurements from the field projects become available, the data will be added to the KB-2 Development.

Summary. Huntsville Center created the OE-GIS as standard methodology for OE project implementation. One GIS module, OE-KB, was developed for data storage and anomaly discrimination. OE-KB provides tools that enable OE site investigators to make well-informed decisions. Those tools integrate and display GIS spatial analysis with OE-KB analytic results. OE-KB incorporates geophysical and project data from multiple sites to promote continual enhancement. Huntsville Center is committed to developing and applying GIS techniques.

Digital Data. By using an Internet browser, you can access this paper and slide presentation from Huntsville Center's home page at *http://www.hnd.usace.army.mil*. When you reach the Center's home page, select *Ordnance and Explosives MCX* to access the OE Mandatory Center of Expertise page. Then select *OE Presentations* to access OE downloadable files. To download a file to your PC, select a presentation, enter the destination on your hard drive, and select *OK*. The presentation will be transferred to your PC. For FTP connection, log onto *155.74.115.80* as *kbase*, password *uxoforum*. There is a directory available for digital documents at *kbdoc* and of computer techniques at *kbtools*. These locations provide the current program and documentation for evaluation.

References: Masters T., 1994, Signal and Image Processing with Neural Networks: John Wiley & Sons, New York.

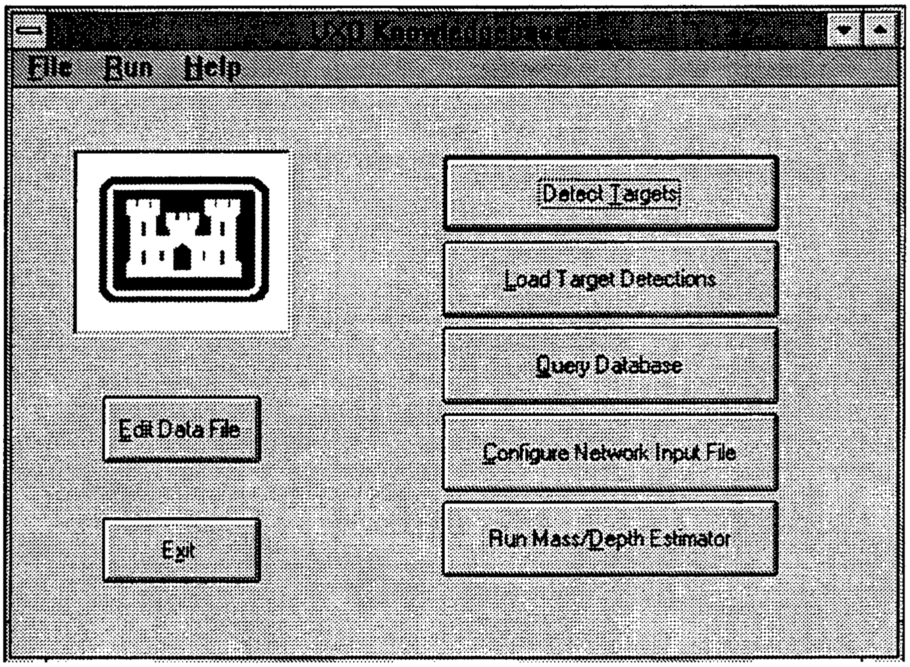

Figure 1. OE-KB Push Button Graphical User Interface

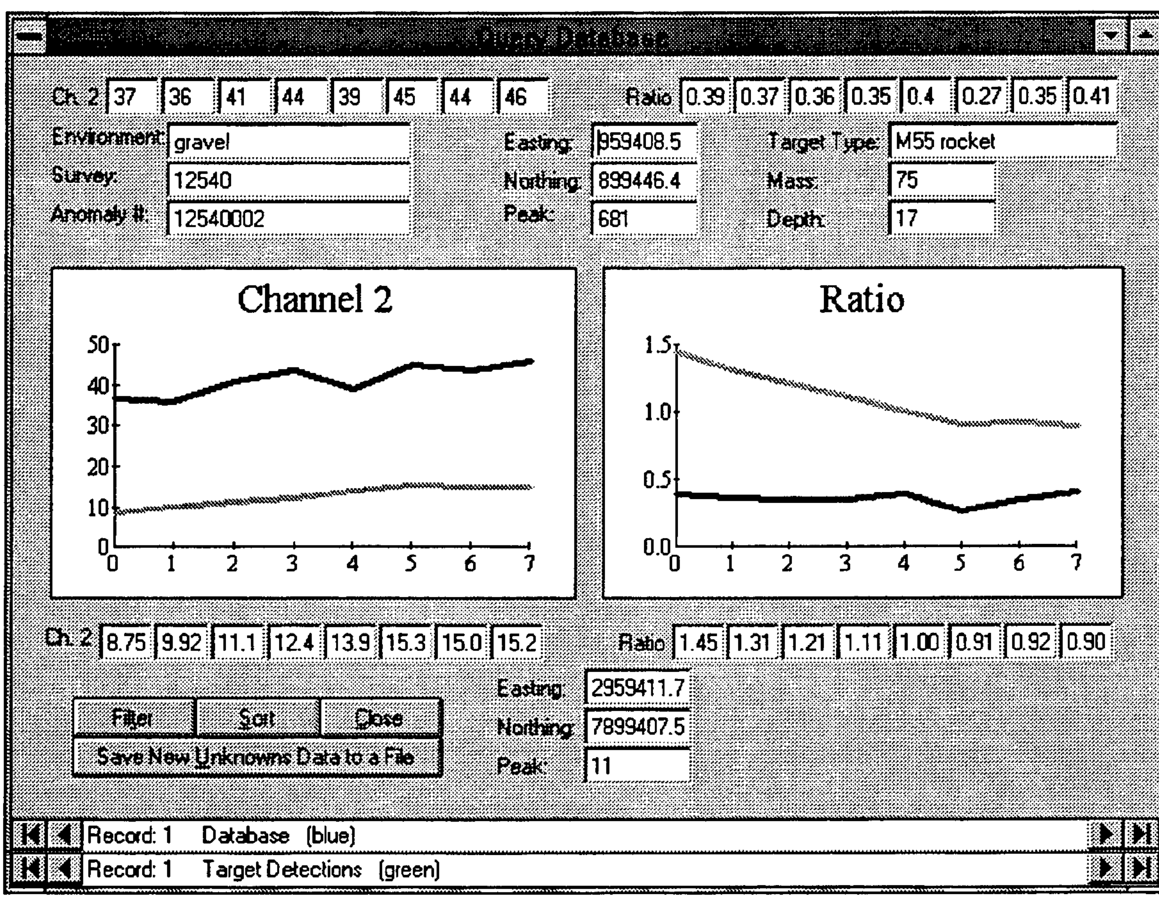

Figure 2. The OE-KB enables the user to scroll through a database of know signatures from identified ordnance items for direct visual comparison. In this example, pulse induction data from Camp Simms, Washington, DC, is shown.

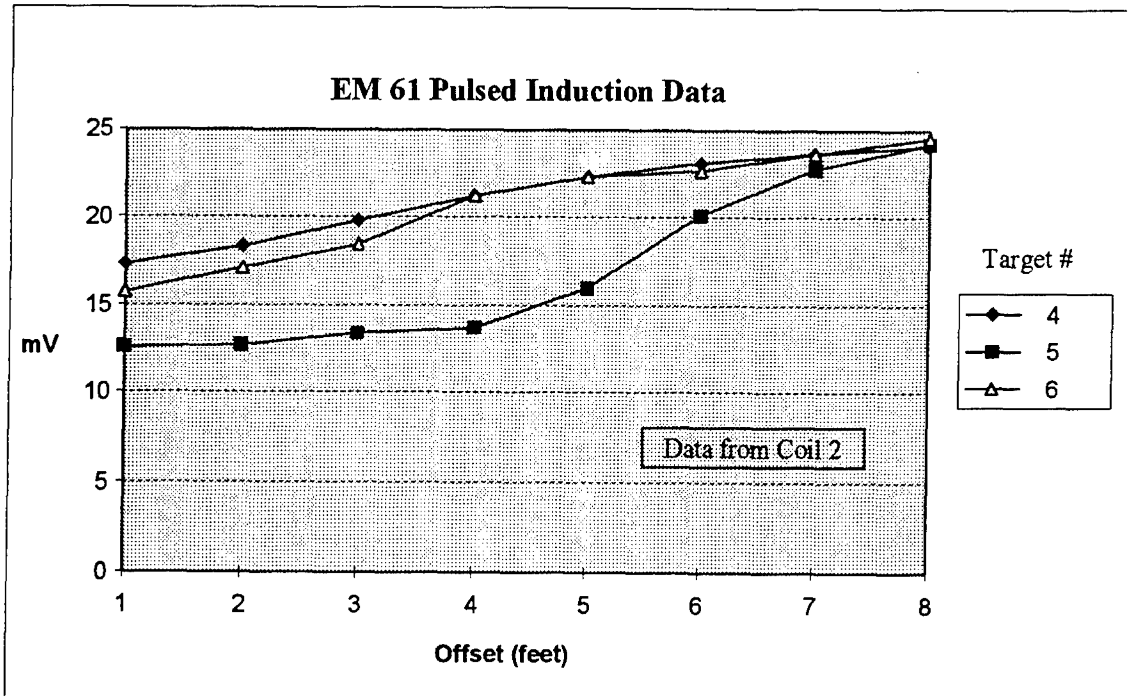

Figure 3. Profile data from a pulse induction sensor over three similar ordnance items.

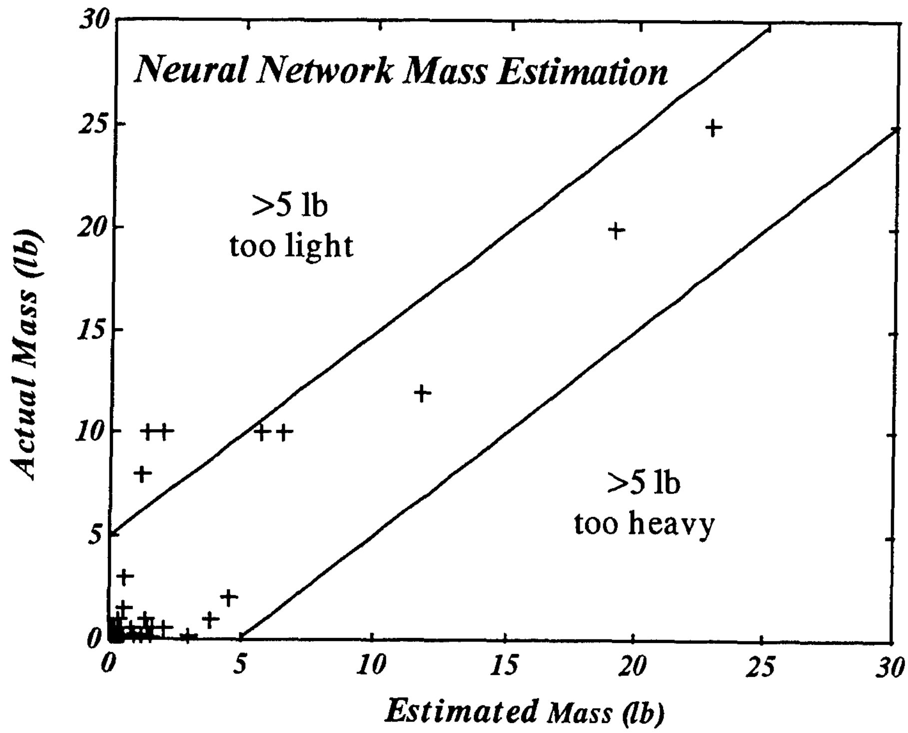

Figure 4. Neural network estimate of target mass compared with actual target mass.

UNEXPLODED ORDNANCE
RISK ASSESSMENT FRAMEWORK

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ABSTRACT

A probabilistic methodology was developed for assessing risk associated with unexploded ordnance (UXO) located in the field. UXO risk is evaluated in terms of three main components, or events, that comprise and define UXO risk. These components are, in sequential order, (1) UXO encounter, (2) UXO detonation, and (3) UXO detonation consequences.

UXO risk is defined as the probability of detonation given an encounter and the distribution of consequences associated with the detonation. The probability of detonation given an encounter is a function of the probability of encounter (P_E) and the conditional probability of detonation (P_D). P_E is the probability that an individual will impart some level of force, energy, motion, or influence on a UXO item. P_D is the probability that a UXO item will detonate once an encounter has occurred. Many variables affect P_E and P_D.

The consequence associated with detonation is conservatively assumed to be serious injury or death. Other consequences are not considered.

The probability distributions resulting from this approach represent the range of risks associated with encountering UXO in the field. This methodology is a work in progress. All UXO risk assessment parameters have not yet been fully evaluated.

METHODOLOGY

Under a probabilistic methodology, risk (R) is a function of the conditional probability distribution of detonation given an encounter (P) and the distribution of consequences associated with the detonation (C), as shown in Equation 1.

$$R \quad f\,[P,C] \qquad (1)$$

For each activity and land use combination, risk is calculated separately for four categories of UXO depth and 29 classes of UXO fuze type. Risk is then aggregated over all UXO depth categories and UXO fuze type classes for each activity and land use combination.

P is a function of the probability of encounter (P_E) and the conditional probability of detonation (P_D), as shown in Equation 2.

$$P \quad f\,[P_E, P_D] \tag{2}$$

Probability of Encounter

The expected number of UXO items encountered (E) is a function of the fraction of the area of concern that is influenced by an activity (L_{jk}/A), the number of UXO items present (D_{ijk}), the number of participants in an activity (N_j), and an individual's awareness of UXO (I), as shown in Equation 3.

$$E \quad f\left[\left(\frac{L_{jk}}{A}\right)(D_{ijk})\,(N_j)\,(I)\right] \tag{3}$$

where

L_{jk}	=	Portion of the area of concern influenced by an activity (j) to a given depth (k)
A	=	Area of concern (The area's size may vary based on site-specific conditions.)
D_{ijk}	=	Number of UXO items of a given fuze type (i) for an activity (j) to a given depth (k) within A. (The distribution of UXO is assumed to be random within A.)
N_j	=	Number of participants in an activity (j)
I	=	Awareness coefficient, or an individual's awareness of UXO that impacts the behavior of that individual (An individual's awareness may be impacted by UXO size, topography, vegetation, soil type, and climate.) (For now, I is assumed to be 1, and the impacts of an individual's UXO awareness on the expected number of encounters will be further investigated.)

A P_E distribution is determined by including a distribution for D_{ijk} because it is unlikely that historical data will be exact and because a range of expert opinions will also be considered. E will be calculated by inputting the mean value for D_{ijk}.

Variables affecting P_E include the following:

- UXO density
- UXO depth
- Activity of an individual
- Awareness of an individual, which can be affected by vegetation, topography, UXO size, soil type, and climate

UXO density within an AOC affects P_E because the greater the number of UXO in an area, the higher the potential for an individual to encounter UXO. Conversely, a low density decreases the potential for an individual to encounter UXO.

UXO depth affects P_E because if a UXO is located beneath the ground surface and if the overlying soil is not disturbed by the individual's activity to the depth of the UXO, then the individual will not encounter the UXO. However, if a buried UXO is located at a depth that is disturbed by a particular activity (for example, plowing) then an encounter may occur.

The nature (type and extent) of an individual's activity determines the percentage of the AOC that is disturbed during the activity. The larger the area disturbed, the higher the potential for the individual to encounter a UXO located within the AOC.

An individual's awareness of the presence of UXO affects the individual's response to the UXO. An individual's response to a UXO can be determined by a human cognitive model. A human cognitive model breaks down the human thought process into the following three controlling parameters: perception, decision making, and action execution. These parameters are aggregated to yield a human reaction time.

An individual's awareness and, therefore, reaction time, is influenced by several factors that collectively impact P_E. One of these factors is vegetation. The amount or type of vegetation present in an area that contains UXO may determine whether an individual can see UXO on the ground surface. Dense vegetation could therefore reduce an individual's awareness of UXO, which would increase P_E.

UXO size is an additional factor affecting an individual's awareness. A large UXO will be more visible to an individual than a small UXO.

Another factor affecting an individual's awareness of the presence of UXO is soil type. Soil type potentially affects the penetration depth of an ordnance item, which in turn affects P_E.

In some cases, climate may affect the individual's awareness of the presence of UXO. For example, in a climate where snow covers the ground, the snow may conceal UXO on the surface. In a rainy climate relatively

small UXO on the surface of steep or rolling terrain may be carried by runoff to low-lying drainage areas such as streams. UXO may accumulate in such areas, increasing UXO density.

Probability of Detonation

P_D is a function of (1) the probability that the activity energy level exceeds the UXO detonation energy level threshold (P_t) and (2) the probability of a detonation given that the activity energy level exceeds the UXO detonation energy level (P_l), as shown in Equation 4.

$$P_D \quad f\,[P_t,\ P_l] \qquad (4)$$

An example matrix showing the relationship between P_t and P_l is presented in Figure 1. In the example matrix, the probability that a detonation will occur corresponds to the shaded area, where the P_t and P_l distributions overlap.

P_D will be determined by eliciting expert opinion regarding the probability distribution of P_D and combining the expert opinion using Bayes' theorem (see Data Collection and Manipulation below).

Variables affecting P_D include the following:

- UXO fuze sensitivity
- Activity of an individual

UXO fuze sensitivity directly affects P_D because the more sensitive the fuze on a particular ordnance, the more likely it is that the fuze will detonate in response to some disturbance. Despite the importance of fuze sensitivity to P_D, data regarding the fuze sensitivity of dud-fired ordnance is very limited.

The activity of an individual affects P_D because the type of activity determines the amount of force, energy, motion, or influence that an individual imparts on an encountered UXO. For example, an activity such as construction would impart a larger amount of force on an encountered UXO than would walking, which generally involves less momentum or force. As with fuze sensitivity, data regarding the amount or type of influence required to activate specific fuzes on dud-fired ordnance is very limited.

Consequences

The consequence associated with detonation (C) is assumed to be the serious injury or death of a person who encounters the UXO item that detonates. Consequences are not further evaluated.

Risk

The probability distributions of P_E and P_D will be input into Monte Carlo simulation software, such as Crystalball©, to develop a probability distribution of risk. Also, the software performs a statistical analysis of the distribution of data, including mean standard error, coefficient of variability, and variance. Therefore, the uncertainty or variability associated with the data set can be quantitatively demonstrated. Thus a distribution of risk values, not an absolute risk value or figure of merit value, will be determined.

Ultimately, mean values of the probability distributions of R can be grouped into five or more categories with associated ranges of risk. The risk category associated with each area of concern can be represented on a color-coded risk map that would visually depict the range of mean risk associated with a site.

Data Collection and Manipulation

Data regarding the fuze sensitivity of dud-fired ordnance and the influence required for fuze activation is very limited. Therefore, these data will be obtained by means of expert opinion elicitation. Expert opinion elicitation is used in the fields of psychology, decision analysis, and statistics as a method of gathering data. Typically, multiple expert opinions are combined to obtain more accurate results than could be derived from the opinion of a single expert. Expert opinion will be used to supplement uncertain or unavailable UXO detonation energy level background data and scant or uncertain historical UXO density data. Questionnaires in the form of matrices would be most effective in eliciting expert opinion. A sample of an expert opinion elicitation matrix is shown in Figure 2. The land use scenarios and depth levels presented in the matrix were taken from the Department of Defense (DoD) guidance regarding reuse of land contaminated with UXO (DoD 1995). A separate matrix is needed for each of the following depth levels: surface, $\leq$ 1 foot below ground surface(bgs), 1 to 4 feet bgs, and 4 to 10 feet bgs.

The expert opinion data set will be combined with the available background or historical data set. However, if the background or historical data is uncertain, Bayes' theorem can be used to update the background or historical data with an expert opinion data set. In short, Bayes' theorem combines the distribution of the two data sets, and therefore no data is discounted. Bayes' theorem for analysis for an uncertain data set is shown in Equation 5 (Winkler 1967).

$$(x\ E_i)\quad \frac{L(E_i\ x)\ \ _0(x)}{L(E_i\ x)\ \ _0(x)dx} \qquad (5)$$

where:

(xE_i)	= Posterior distribution of x given E_i
$_0(x)$ =	Prior distribution of x
$L(E_ix)$	= Likelihood of E_i given x
E_i	= i^{th} interpretation of data

Also, Bayes' theorem can be used to combine the distribution of more than one expert opinion data set. For example, by asking the experts questions with known answers, a confidence level for each expert can be developed based on the expert's bias. Thus, expert bias is taken into consideration in combining expert opinion data sets. Bayes' theorem for combining expert opinion data sets is shown in Equation 6 (Winkler 1967).

$$(x\ E\ )\quad k^{\ 1}\ L(E\quad x)\ \ (x) \qquad (6)$$

where

(x E)	=	The posterior state of knowledge about the unknown quantity, x, after the set of expert opinions, E*, is received
k	=	A normalization factor that makes (x E) a probability distribution
E*	=	The set of expert opinions about the value of x
L(E x)	=	The likelihood of the evidence E* given that the true value of the unknown quantity is x
(x)	=	The state of knowledge about the unknown quantity x prior to receiving expert opinions

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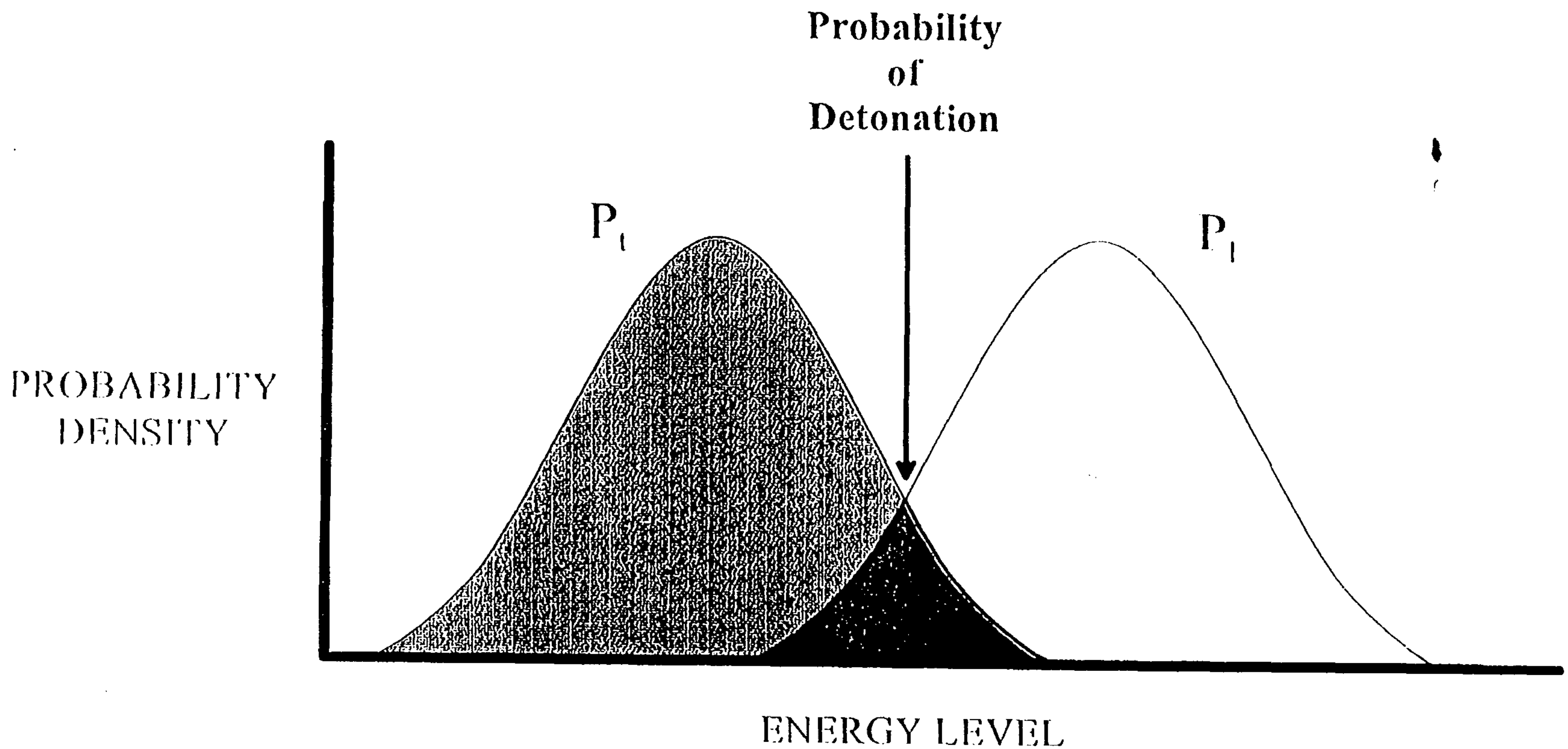

FIGURE 1. PROBABILITY OF DETONATION

PROBABILITY
OF
DETONATION

	SURFACE		SHALLOW (0 TO 1')		DEEP (1' TO 4')		VERY DEEP
	Light	**Heavy**	**Light**	**Heavy**	**Light**	**Heavy**	**4' to 10'**
	HIKING	VEHICLE TRAV	GRADING	FARMING	ARCHEOLOGY	CONSTRUCTION	DRILLING
	walking		LIVE STOCK		ARGRICULTURE		CONSTRUCTION
ORDNANCE FUZED WITH							
Chemical Long Delay Booby-Trap							
Time Delay (Submunitions)							
Mechanical Time (MT)							
Mechanical Time Super Quick (MTSQ)							
Point Detonating Self-Destruct (PDSD)							
Point Detonating (40mm Grenades)							
Impact Inertia (Submunitions)							
Mechanical All Ways Acting							
Electrical All Ways Acting							
Impact inertia (bombs)							
Impact (Submunitions)							
Pull (Land Mines)							
Pressure Release (Land Mines)							
Pressure (Anti-Personnel Land Mines)							
Pressure (Anti-Tank Land Mines)							
Mechanical Clockwork Long Delay							
Piezo-Electrical (PIBD-L)							
Striker Release (Grenades)							
Point Detonating (PD)							
Point Initiating Base Detonating "Spit-Back" (PIBD)							
Time Super Quick (TSQ)							
Base detonating							
Powder Train Time Fuze (PTTF)							
Pull-Friction (Grenades)							
Electronical Time (Projectiles)							
Electrical Delay (Grenades)							
Proximity (VT)							
Influence							
Electronical Long Delay Anti- disturbance							
None (Armor Piercing)							

RISK ASSESSMENT METHODOLOGY FOR USE IN MANAGING SITES CONTAINING UNEXPLODED ORDNANCE

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INTRODUCTION

This paper describes the development of a method for assessing risks presented by unexploded ordnance (UXO). The method was developed by the U.S. Army Environmental Center (USAEC) for use at Fort George G. Meade (FGGM), MD, a Base Realignment and Closure (BRAC) installation. This method was developed to evaluate the UXO risk present at this site and to form the basis for risk management decisions with the goal of creating an acceptably safe reuse of the property as a wildlife refuge. The theory of this approach is based on traditional human health risk assessment methods modified to reflect UXO exposures and evaluations. The risk assessment method uses both deterministic and probabilistic risk estimation techniques and uses a variety of land reuse and exposure scenarios. Additionally, this study presents an evaluation of estimated risk reduction gained from UXO removal actions. In this case, this evaluation quantifies the risk reduction expected from different UXO removal programs including no action, removal of UXO up to six inches in depth and a twelve inch removal. The results of this comparative evaluation can be used to evaluate and determine appropriate UXO removal depths to allow for safe reuse of the property.

BACKGROUND

FGGM formerly encompassed 13,536 acres and has operated as a U.S. Army installation since 1917. In 1988, approximately 9,000 acres of FGGM were designated as a BRAC parcel and the USAEC began an enhanced preliminary assessment (EnPA) to determine the environmental condition of the BRAC parcel. This parcel historically had been used as range and training lands that contain a variety of munitions and UXO. The EnPA identified UXO as a concern on the BRAC parcel (Argonne. 1989). The USAEC responded by undertaking a UXO survey to describe the location, quantity and type of UXO remaining on the BRAC parcel. This action included location, identification and removal of UXO to a depth of 6" below land surface (BLS) over the entire BRAC parcel.

Legislation mandated the transfer of 8,100 acres of the FGGM BRAC parcel to the U.S. Department of Interior (DOI) for use as a wildlife refuge. As a result the U.S. Army and the U.S. Department of Interior entered into an agreement to transfer these lands to the Patuxent Environmental Science Center (PESC). PESC assumed control of the lands while the Army's environmental restoration of the property continued. Prior to the completion of the property transfer agreement, the USAEC began the UXO survey of the BRAC parcel. The land transfer agreement between the U.S. Army and DOI included specific requirements related UXO removal actions. In general, the transfer agreement indicates that the Army shall locate and remove UXO to a depth of 12" BLS. Since the USAEC's survey specified a 6" BLS location and removal it became necessary to evaluate the benefit of additional UXO removals to the 12" BLS depth

as specified in the transfer agreement.

Lacking a specific tool to make such a determination we undertook a project to develop a method, specific to the FGGM environmental restoration program, that could be used in evaluating UXO risks related to variety of reuse scenarios, differing concentrations of UXO and a variety of removal depths. To do this we initiated an effort to develop and implement a probabilistic risk assessment and effectiveness evaluation to estimate risk related to UXO considering PESC's planned and continuing reuse of the parcel as a wildlife refuge, USAEC's initial UXO 6" survey efforts, and an estimation of the UXO remaining after a 12" removal.

METHOD DEVELOPMENT

In developing the risk assessment and effectiveness evaluation tool we first needed to define the receptor's exposure endpoint. In the initial stages of the method development we gave much consideration to modeling a variety of endpoints, however, lacking definitive empirical or epidemiologic data to develop exposure and effect relationships we opted for a single simple exposure endpoint. This risk assessment endpoint is best described as a single contact of any type with the subject UXO. Thus, for the exposure endpoint to be reached a receptor must have his physical path (footstep, bike-tread, etc.) must be imposed over a UXO item. In the primary evaluation, the risk of exposure to UXO is defined as the probability that a receptor will encounter at least one UXO per day of activity.

Additional factors that were considered in the model development included, but were not limited to, depth of ordnance, type of ordnance and soil type. These included factors that could be used to better describe the actual risk related to our chosen exposure endpoint. Here too, just as with the exposure and effects relationships, there seemed to be a lack of definitive data or tools that would allow for inclusion of these factors within this risk assessment.

Finally, considering the receptors, we used visitor statistics from PESC and subsequently were able to categorize these visitors within distinct activity groups that could be evaluated in the exposure assessment. These categories are walking, jogging, biking, hunting, fishing, group activities (e.g. camping) and working. In the end, the simple form of the risk assessment becomes a function of the distribution density of the UXO and the specific receptor category.

To apply the model we developed two types of risk estimates. The first of these estimates is a common single point deterministic estimate that is used to derive conservative single point risk estimates. The second estimate is the probabilistic assessment and actually is best viewed as a range of possible outcomes. In the probabilistic assessment a Monte Carlo simulation was used to generate a distribution of possible values for the input parameters of the risk assessment. The outcome of this probabilistic method is then used to interpret the deterministic results.

Additionally, an effectiveness evaluation was performed as an extension of the risk evaluation model. Primarily the effectiveness is measured by two indicators:

1. Reduction in risk achieved by the original 6" BLS survey, and

2. Estimation of additional risk reduction gained by a 12" BLS removal.

The study area was divided into subareas that are used in managing the PESC property. Within each of these subareas the distribution of UXO is considered to be random and relatively homogeneous. Under this assumption the Poisson distribution best describes the random spatial distribution of the UXO. Relating the Poisson "process" to UXO distribution yields the following properties:

1. The number of UXO is the defined subareas is independent of the number that occurs in any other area,

2. The probability of finding ordnance in a very small area is proportional to the size of the area and does not depend on the number of UXO found outside that small area, and

3. The probability that more than one UXO will be found is a very small area is considered negligible.

The number of UXO found in a given area is treated as a Poisson random variable and forms the basis of the risk characterization equations as follows.

The risk of contacting a UXO within a given subarea is derived as follows. The receptor's path is assumed to contact "a" square feet within the k^{th} subarea of "A(k)" square feet ($A <= A(k)$), and that there as "s_k" UXO in the subject subarea. The probability that the receptor

avoids a UXO is given by:

$$1-\frac{a}{A(k)}$$

and the probability that the receptor avoids all "s_k" UXO in that subarea is

$$(1-\frac{a}{A(k)})^{a_k}$$

If we define risk as the probability that the receptor does not avoid all UXO. That is equal to 1 minus the previous equation, or

$$R_k(a)=1-(1-\frac{a}{A(k)})^{a_k}$$

The number of UXO, "s_k" in the "k^{th}" subarea is unknown and estimated by multiplying that average number per acre, "m_k", found in the sampled grids by the total acreage of the subarea k (or $s_k = m_k A(k)$). Substituting into the previous equation gives estimated risk as

$$R_k(a)=1-(1-\frac{a}{A(k)})^{m_k A(k)}$$

Furthermore, when the risk is small, the nonlinear formula can be closely approximated by a linear form analogous to the conventional EPA low-dose extrapolation risk assessment equation, as

$$R_k=1-(1-\frac{a}{A(k)})^{s_k}=\frac{s_k a}{A(k)}$$

IMPLEMENTATION

Data collection for the risk assessment was accomplished by a statistically based UXO survey of the land parcel. The object of the sampling design was to collect sample data on the numbers, type, depths and locations of UXO in order to develop unbiased estimates and confidence limits for the risk assessment and effectiveness evaluation. To accomplish this we adopted a systematic random grid sample design commonly used in spatial sampling (Ripley, 1981). Specifically in this case we designed a survey of 240 1/8 acre sample areas for a total sample area of 30 acres. The locations of the sample areas were determined by the nodes of a triangular grid pattern that was randomly superimposed over a map of the BRAC parcel. This method ensured that every surface unit had an equal probability of being sampled.

RESULTS

At the conclusion of the field effort the data was compiled and both the single point (deterministic) and probabilistic risk estimates were calculated. Table 1. below presents results of the calculations used to estimate the UXO density (or concentration) in the different geographical subareas in units of UXO per acre. The probabilistic estimates are represented by the upper and lower 80% confidence limit. The maximum point estimate of UXO concentration is 2.84 UXO per acre for the 0" to 12" interval while the minimum point estimate approaches 0 UXO per acre in that same 0" - 12" interval. Similarly Table 2. presents the same type data, however, in this case the concentration estimates exclude small arms data. Here the maximum concentration is 2.29 and the minimum again approaches 0 UXO per acre.

Table 3 presents the results of the deterministic risk estimates geographic subunit 1 and includes the small arms data. These risk estimates range from near 1.00 to 0.0066 likelihood of an exposure during one day of activity. Table 4 presents the same type deterministic estimates while excluding the small arms data. Here the risk estimates range from 1.00 to 0.0066 likelihood of exposure per day of activity.

Tables 5, 6 and 7 present a sample of the probabilistic risk estimates while discriminating between UXO data related to surface, 0" - 6" BLS, and 0" - 12" BLS respectively. In these estimates the risk ranges from 0.99 to 0.0044 likelihood of an exposure per day of activity.

CONCLUSION

The risk assessment methodology described herein was developed to aid in the management of the UXO program of the BRAC lands transferred to PESC. To do this we have developed this method of evaluating risks relating

UXO presence and reuse. The risk assessment method only looks at the relationship between the presence of UXO and likelihood of exposure and does not make any finite distinctions between type of ordnance, depth of ordnance and likelihood and outcome of exposure to UXO. As such, the results present a worst-case risk estimate for exposure to UXO for likely land use scenarios. The risk estimates are presented as the probability of encountering one UXO item per day of activity in a matrix of different land uses (or receptor categories) and geographic subdivisions. Actual or most probable risks are expected to be significantly, possibly orders of magnitude lower than those presented in this model.

The calculated risks estimates are presented in both a deterministic and probabilistic form as generated from the statistical estimation of UXO concentration and use of exposure descriptor data. The final results are presented in a form that allows finite comparisons between the different levels of UXO removal effort and reuse scenarios.

Application of this risk assessment model may be possible at other sites. However, careful consideration must be given in the development of the sampling program, establishment of exposure descritor factors and choice of receptor categories.

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Table 1. Estimated UXO Concentration by Subarea Unit, Small Arms Data Included

Subarea Sampled Grids Acreage	Depth	Lower 80% Confidence Limit	Point Estimate (UXO/Acre)	Upper 80% Confidence Limit
Unit 1: ASP, D, E 42 1754	Surface <=6" <=12"	0.02 1.18 1.49	0.19 1.90 2.29	0.74 2.93 3.39
Unit 2: F 28 1134	Surface <=6" <=12"	0 0 0	0 0 0	0.66 0.66 0.66
Unit 3: G,H,K,L 36 1385	Surface <=6" <=12"	0 0.12 0.39	0 0.44 0.89	0.51 1.18 1.78
Unit 4: J,M,I 40 1319	Surface <=6" <=12"	0 0.35 0.35	0 0.80 0.80	0.46 1.60 1.60
Unit 5: N,O,DZ,V,W,X,Y 45 1444	Surface <=6" <=12"	0 0.83 0.97	0 1.42 1.60	0.41 2.31 2.53
Unit 6: P,Q,R,S,T,U 31 1160	Surface <=6" <=12"	0.28 1.81 1.81	0.77 2.84 2.84	1.72 4.28 4.28
Unit 7: Airfield 14 700	Surface <=6" <=12"	0 0 0	0 0 0	1.31 1.31 1.31
Total 236 8895	Surface <=6" <=12"	0.06 0.94 1.09	0.14 1.19 1.36	0.27 1.49 1.68

Table 2. Estimated UXO Concentration by Subarea Unit Type, Small Arms Excluded

Subarea Sampled Grids Acreage	Depth	Lower 80% Confidence Limit	Point Estimate (UXO/Acre)	Upper 80% Confidence Limit
Unit 1: ASP, D, E 42 1754	Surface <=6" <=12"	0.02 1.18 1.49	0.19 1.90 2.29	0.74 2.93 3.39
Unit 2: F 28 1134	Surface <=6" <=12"	0 0 0	0 0 0	0.66 0.66 0.66
Unit 3: G,H,K,L 36 1385	Surface <=6" <=12"	0 0.02 0.12	0 0.22 0.44	0.51 0.86 1.18
Unit 4: J,M,I 40 1319	Surface <=6" <=12"	0 0.11 0.11	0 0.40 0.40	0.46 1.06 1.06
Unit 5: N,O,DZ,V,W,X,Y 45 1444	Surface <=6" <=12"	0 0.20 0.20	0 0.53 0.53	0.41 1.19 1.19
Unit 6: P,Q,R,S,T,U 31 1160	Surface <=6" <=12"	0.14 0.81 0.81	0.52 1.55 1.55	1.37 2.72 2.72
Unit 7: Airfield 14 700	Surface <=6" <=12"	0 0 0	0 0 0	1.31 1.31 1.31
Total 236 8895	Surface <=6" <=12"	0.04 0.52 0.64	0.10 0.71 0.85	0.23 0.96 1.11

Table 3. Deterministic Risk Assessment Results including Small Arms (Geographical Unit 1)

Receptor	Surface	0"-6"	0"-12"	0-18"
Walker	0.095	0.67	0.73	0.73
Jogger	0.014	0.81	0.86	0.86
Biker	0.20	0.92	0.95	0.95
Hunter - Unsuccessful	0.014	0.14	0.16	0.16
Hunter - Successful	0.040	0.36	0.41	0.41
Fishman	0.0066	0.070	0.082	0.082
Worker	0.37	0.99	1.00	1.00

Table 4. Deterministic Risk Assessment Results excluding Small Arms (Geographical Unit 1)

Receptor	Surface	0"-6"	0"-12"	0-18"
Walker	0.095	0.55	0.63	0.63
Jogger	0.014	0.70	0.78	0.78
Biker	0.20	0.84	0.90	0.90
Hunter - Unsuccessful	0.014	0.10	0.13	0.13
Hunter - Successful	0.040	0.28	0.34	0.34
Fishman	0.0066	0.051	0.064	0.064
Worker	0.37	0.97	0.99	0.99

Table 5. Example of Probabilistic Risk Assessment Results, Surface UXO (Geographical Subunit 1, excluding small arms)

Activity	50th Percentile	95th Percentile	Best Estimate
Walking	0.067	0.18	0.095
Jogging	0.074	0.23	0.14
Biking	0.25	0.62	0.20
Hunting - Unsuccessful	0.011	0.030	0.014
Hunting - Successful	0.028	0.082	0.040
Fishing	0.0044	0.014	0.0066
Working	0.18	0.39	0.37

Table 6. Example of Probabilistic Risk Assessment Results, 0"- 6" UXO (Geographical Subunit 1, excluding small arms)

Activity	50th Percentile	95th Percentile	Best Estimate
Walking	0.39	0.65	0.55
Jogging	0.43	0.75	0.70
Biking	0.88	0.99	0.84
Hunting - Unsuccessful	0.072	0.14	0.10
Hunting - Successful	0.18	0.35	0.28
Fishing	0.031	0.072	0.051
Working	0.74	0.91	0.97

Table 7. Example of Probabilistic Risk Assessment Results, 0"-12" UXO (Geographical Subunit 1, excluding small arms)

Activity	50th Percentile	95th Percentile	Best Estimate
Walking	0.44	0.71	0.63
Jogging	0.48	0.80	0.78
Biking	0.92	1.00	0.90
Hunting - Unsuccessful	0.091	0.17	0.13
Hunting - Successful	0.21	0.40	0.34
Fishing	0.037	0.085	0.064
Working	0.80	0.95	0.99

Installation Management of Recovered Chemical Warfare Materiel

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ABSTRACT

During the past two decades, the U.S. Army has discovered significant quantities of buried chemical warfare materiel at multiple locations throughout the United States. These items, because of their differing configuration and condition, present unique characterization challenges, a prerequisite to safe and efficient disposal. Fundamental characterization challenges include positive identification of the chemical agent fills and determination of explosive configurations. Recovered items range from obsolete Chemical Agent Identification Sets (containing dilute quantities of chemical agents and surrogate chemical agents) to suspect chemical agent filled explosively configured munitions of unknown origin that may have been buried more than 30 years.

Pine Bluff Arsenal, Arkansas became a participant in the management and disposal of recovered chemical warfare materiel at the close of World War II when chemical weapons captured from German forces were transported to Pine Bluff Arsenal for intelligence evaluation and disposal. Contemporary (circa 1950) disposal practices included chemical neutralization (and sometimes burning) and burial of the items in trenches or pits. Cleanup of all confirmed chemical burial sites at Pine Bluff Arsenal occurred in the 1970s and 1980s. These pioneering remediation efforts resulted in the development of recovery expertise and management practices applicable to recovered chemical warfare materiel. Recovered chemical warfare materiel items are currently stored in earth covered igloos, visually inspected, and air monitored utilizing absorptive sample collection methods and Gas Chromatography/Mass Spectroscopy sample analysis.

Upon determination of the magnitude of remediation and disposal challenges facing the Department of Defense, the Army established and resourced the Project Manager for Non-Stockpile Chemical Materiel to manage, direct, and accomplish the dynamic recovery and cleanup challenges. The Project Manager for Non-Stockpile Chemical Materiel called upon Pine Bluff Arsenal to be an active partner in the Army's development and execution of disposal plans, procedures, and technologies. In the winter of 1993, a housing developer in the Spring Valley area of Washington, D.C. accidentally discovered old chemical munitions. Pine Bluff Arsenal personnel supported the recovery and remediation of the suspect chemical weapons. Buried chemical warfare materiel, dating from World War I, was safely removed from the Spring Valley burial sites, preliminarily examined on-site, packaged and transported to Pine Bluff Arsenal for safe storage pending the fielding of treatment or disposal equipment.

Spring Valley operations, and ongoing research and development efforts managed by the Project Manager for Non-Stockpile Chemical Materiel, demonstrated the potential and successful application of contemporary non-intrusive inspection technologies toward the characterization of recovered chemical warfare materiel. As a part of field operations, contemporary non-intrusive inspection technologies have been integrated into the recovery process, to include: chemical agent air monitoring, Portable Isotopic Neutron Spectroscopy, and radiographic inspections.

Enhanced characterization of the recovered chemical warfare materiel items was determined to be prerequisite to safe and efficient disposal operations; however, fully effective application of the non-intrusive inspection technologies requires direct access to the items to be inspected. Recovered chemical warfare materiel items that were previously in storage were placed in overpack containers; thereby, denying direct access to the items and prohibiting the fully effective use of non-intrusive testing. To accomplish recovered chemical warfare materiel inspection objectives, it was determined that a custom built facility incorporating inspection equipment, environmental engineering controls, and security features should be constructed and operated at Pine Bluff Arsenal to ensure

worker, public, and environmental safety during these operations.

The recovered chemical warfare materiel examination facility, currently under design, will incorporate controlled and filtered ventilation, unpacking and repacking capability, non-intrusive enhanced inspection capability (i.e., Visual, Portable Isotopic Neutron Spectroscopy, and radiography), and data collection equipment. Upgrading and utilizing the existing structures at Pine Bluff Arsenal was determined to be an acceptable and cost effective approach to satisfying facility requirements. Safety was the primary criterion for selecting a facility and location; after satisfying human and environmental safety considerations, the cost of construction and operation were also included as selection criteria. A seven factor decision matrix was created to identify and optimize the selection of acceptable facilities and locations, as follows: safety requirements, environmental considerations, security requirements, facility selection, site selection, site terrain, and utility availability. The optimum facility decision resulted in selection of a pair of existing igloos in a remote region of Pine Bluff Arsenal.

Construction and operations will be accomplished by a team comprised of both government and contractor personnel. Construction and operational efficiencies will be recognized by establishing a self-sufficient facility with the potential to host planned on-site treatment systems. The Examination Facility at Pine Bluff Arsenal will enhance the Army's responsiveness and provide life-cycle management capability for recovered chemical warfare materiel.

INSTALLATION HISTORY

A few weeks before the Japanese attack on Pearl Harbor, ground was broken for the original construction of the 5,000 acre Pine Bluff Arsenal complex. Seven months later, in July of 1942, actual production began. Soon thereafter, to support increasing soldier needs in the field, production capabilities of the original facility was increased, resulting in a site expansion to 15,000 acres. Since the original production of incendiary munitions began at Pine Bluff Arsenal, many conventional munitions and chemical warfare materiel items have been produced. Unitary chemical warfare materiel production ended in the 1960s. Binary chemical warfare materiel production was halted in the 1980s. Conventional munition production continues to this day.

Pine Bluff Arsenal, Arkansas became a participant in the management and disposal of recovered chemical warfare materiel at the close of World War II when chemical weapons captured from German forces were transported to Pine Bluff Arsenal for intelligence evaluation and disposal. Contemporary (circa 1950) disposal practices included chemical neutralization (and sometimes burning) and burial of the items in trenches or pits.

Contemporary chemical demilitarization efforts at Pine Bluff Arsenal began with construction of the incapacitating agent BZ Demilitarization Facility in 1984. BZ Demilitarization Facility construction and testing was completed in 1988. Chemical agent BZ disposal operations and facility closure were completed in 1990. The facility was the Army's first production scale government owned and contractor operated facility. The safe and efficient accomplishment of this mission demonstrated the successful partnership of overall project management by the Army Program Manager for Chemical Demilitarization, facility construction management by the Army Corps of Engineers, construction and operations contractors, and security, transportation, and operations management by Pine Bluff Arsenal.

In addition to storing recovered chemical warfare materiel, which will be destroyed as part of the Army Non-Stockpile Chemical Materiel Project, Pine Bluff Arsenal is one of nine sites currently storing the United States stockpile of unitary chemical munitions. Pine Bluff Arsenal is currently supporting planning and environmental permitting of facilities to destroy the unitary chemical stockpile items as part of the Army Chemical Stockpile Disposal Project.

INSTALLATION REMEDIATION

Cleanup of all confirmed chemical burial sites at Pine Bluff Arsenal occurred in the 1970s and 1980s. These pioneering remediation efforts resulted in the development of recovery expertise and management practices applicable to recovered chemical warfare materiel.

The majority of recovered chemical warfare materiel items stored at Pine Bluff Arsenal were the product of one site, identified as Site 12, within an installation remediation project. A consent agreement between the State of Arkansas and Pine Bluff Arsenal resulted in a 1986 environmental project entitled Hazardous Landfill/Closure Sites. The project was approved for Army Corps of Engineers administration and contractor execution.

The results of core drilling samples indicated that there were contaminants, heavy metals, and likelihood of encountering munitions in subsequent closure operations at Site 12, one of 20 similar sites. However, no chemical agent was encountered during sampling of Site 12. Site 12 operations

began in May 1988. In June, contractor personnel uncovered items including German tractor rockets, 4.2 inch mortar rounds, and glass vials from chemical identification sets.

Pine Bluff Arsenal personnel including the U.S. Army Explosive Ordinance Detachment and U.S. Army Technical Escort Detachment recovered, decontaminated, containerized and stored all potential chemical warfare materiel. Due to the increased magnitude of the operations, Pine Bluff Arsenal submitted an update to the original site plan and provided a detailed description and assessment of ongoing and proposed operations. Site 12 operations resulted in the recovery of several hundred items, including: 4.2 inch mortars, German tractor warheads, German tractor rockets, M1 war gas ID sets, a 200mm Livens Projector, a 105mm cartridge, a 155mm projectile, and bottles/vials.

Track hoes and dozers were used to excavate the pits at Site 12. Munitions that were recovered were field tested for leaks and presence of agent, placed inside plastic bags, wrapped and taped, and then placed in another plastic bag and taped. The double bagged and wrapped munitions were then placed in epoxy lined barrels and surrounded by vermiculite. In addition, all leaking munitions and contaminated glass and metal scrap were decontaminated, sealed and double wrapped in plastic, and stored in barrels separate from non-leaking items.

Extensive soil and debris sampling of Site 12 and complete lab analysis was conducted throughout the remediation effort. In addition to the intact munitions, a sweep of the area surrounding Site 12 was conducted and approximately 60 cubic yards (39,000 pounds) of scrap metal was collected. The scrap metal consisted of miscellaneous bomb, mortar, and projectile casings. All items were inspected by the U.S. Army Explosive Ordinance Division and found to be free of explosive materiels. A chemical survey was performed by the U.S. Army Technical Escort Unit and all items were determined to be free of chemical agent fill. In addition to gross level field chemical agent contamination inspection, the items were analyzed by the Pine Bluff Arsenal laboratory for presence of chemical agents; all lab tests results were negative.

STORAGE OF CHEMICAL WARFARE MATERIEL

Recovered chemical warfare materiel items are currently stored in overpack containers inside earth covered igloos, visually inspected, and air monitored utilizing absorptive sample collection methods and Gas Chromatography/Mass Spectroscopy sample analysis.

TECHNOLOGY EVOLUTION

Spring Valley remediation operations in early 1990s, and ongoing research and development efforts managed by the Project Manager for Non-Stockpile Chemical Materiel, demonstrated the potential and successful application of contemporary non-intrusive inspection technologies toward the characterization of recovered chemical warfare materiel. As a part of field operations, contemporary non-intrusive inspection technologies have been integrated into the recovery process, to include: chemical agent air monitoring, Portable Isotopic Neutron Spectroscopy, and radiographic inspections.

CHARACTERIZATION OF RECOVERED CHEMICAL WARFARE MATERIEL

Enhanced characterization of the recovered chemical warfare materiel items was determined to be prerequisite to safe and efficient disposal operations. Useful application of the non-intrusive inspection technologies requires direct access to the items to be inspected. Recovered chemical warfare materiel items that were previously in storage at Pine Bluff Arsenal were placed in overpack containers; thereby, denying direct access to the items and prohibiting the fully effective use of non-intrusive testing. To accomplish recovered chemical warfare materiel inspection objectives, it was determined that a custom built facility incorporating inspection equipment, environmental engineering controls, and security features should be constructed and operated at Pine Bluff Arsenal to ensure worker, public, and environmental safety during these operations.

As an integral part of the overall goal to dispose of the recovered chemical warfare materiel at Pine Bluff Arsenal, the Project Manager for Non-Stockpile Chemical Materiel and Pine Bluff Arsenal began the development of plans and specifications for a facility capable to support safe unpacking, inspecting, identifying, labeling, and repacking of recovered chemical warfare materiel. In addition to accomplishing the above listed examination tasks, the NSCM Examination Facility would also include the potential for addition of the infrastructure necessary to support planned on-site treatment system operations (i.e., Rapid Response System (RRS), Munitions Management Device One, and Munition Management Device Two).

NSCM EXAMINATION FACILITY SITE SELECTION

Safety was the primary criterion for selecting the facility and location; after satisfying human and environmental safety considerations, the cost of construction and

operations were included in the analysis. A seven factor qualitative decision matrix was created to identify and optimize the selection of acceptable facilities and locations, as follows (the factors were ordered to reflect their hierarchy of consideration): safety requirements, environmental considerations, security requirements, facility selection, site selection, site terrain, and utility availability.

Upon conceptual definition of general facility requirements, extensive investigation, and multiple site visits, three (3) potential sites were selected for establishment of the NSCM Examination Facility. Utilization of existing igloo structures was determined to be the most realistic and cost effective approach to satisfying project facility requirements. The potential sites were presented to management, decision bases and preferences discussed, and a site selected. The optimum facility decision resulted in selection of a pair of existing igloos in a remote region of Pine Bluff Arsenal, known as the North Igloo Area, and identified in the matrix below as Site A.

NSCM EXAMINATION FACILITY LOCATION DECISION MATRIX

Evaluation Factors	Site A	Site B	Site C	Site D
Safety Requirements	+	+	+	-
Environmental Considerations	0	0	0	0
Surety Requirements	+	+	+	-
Facility Selection	+	+	+	-
Site Selection	0	0	0	Not Applic able
Terrain and Site Preparation	+	-	-	Not Applic able
Utility Availability	0	0	0	Not Applic able

Safety Requirements

Safe chemical demilitarization and explosive ammunition operations have been and continue to be conducted at Pine Bluff Arsenal. NSCM recovered chemical warfare materiel storage and examination operations include inherent risks (risk is fundamentally the product of probability and consequences) that require mitigation to acceptable levels. Fundamental risk reductions were achieved as part of the site selection and conceptual operating scenario definition processes, as follows:

It was determined that long-term storage of the recovered chemical warfare materiel will remain at the existing storage location within the high security storage area. Long-term storage within the high security area igloo structures reduced potential accident risk probabilities by providing enhanced security of the recovered chemical warfare materiel that would not ordinarily be required at other storage locations.

Existing igloo structures, other existing facilities, and new facilities were conceptually considered for use as interim storage and examination operation facilities. The existing igloo structures were determined to provide inherent containment and external event protection. In addition, they were determined to possess favorable physical configurations. Potential risk consequences were reduced by the igloo structure containment features and the reduction of the potential for external event generated accidents.

Gross area evaluations, including transportation distances and site remoteness, resulted in consideration of existing igloo structures in the North Igloo Area. The North Igloo Area is relatively isolated and has limited activity as a part of on-going storage and transportation operations. It was concluded that the inherent inactivity in the North Igloo Area enhances safety by limiting possible interferences with or potential accidents involving other operations and personnel. Sites within the North Igloo Area were evaluated in detail. Explosive intraline and inhabited building distances were determined to define potential NSCM Examination Facility operational restrictions and impacts on surrounding storage igloos, administration areas, and the general public. Calculations were conducted to determine the maximum explosive quantity of Pine Bluff Arsenal production items that feasibility could be placed inside a North Igloo Area igloo structure. It was concluded, that there would be no adverse effects on the quantity of production items (Class 1.2, 1.3, and 1.4 materials) which could potentially be stored within surrounding igloos. Potential accident probabilities were reduced by selecting a site close to existing storage areas that limited transportation distances. Existing igloo locations were evaluated to determine locations that provided the greatest distance

between potential facility sites, other operations, and the off-post community. Potential accident consequences were reduced by selecting remote transportation routes and sites.

Environmental Considerations

All potential sites were qualitatively determined to have equal accident free operational impacts. Utilization of existing structures, in previously developed areas, was determined to be the only significant and definable environmental site selection criteria. It was concluded that utilization of existing facilities in previously developed areas provided the least environmental impact. All other environmental considerations were determined to be equivalent for all potential Pine Bluff Arsenal sites.

Surety Requirements

Army Regulation, AR 50-6, classifies recovered chemical warfare materiel as hazardous waste, to be managed in compliance with environmental laws and regulations, and excludes recovered chemical warfare materiel from the requirements of Army Surety regulations. Consideration was given to locating the Examination Facility within the existing high security chemical agent storage area, denoted in matrix as Site D; however, due to the non-surety status of recovered chemical warfare materiel, it was determined that locating the facility elsewhere would result in a facility that was safer and less costly to construct and operate.

Facility Selection

Utilization of both single and double-door igloos were considered. Selection of an igloo with double-doors was determined to be necessary to allow maximum utilization of prefabricated material handling, containment, and examination equipment. It was concluded the utilization of double-door igloos would be advantageous, maximizing the opportunity for efficient shop fabrication of process equipment and limiting site assembly labor requirements for installation of process equipment within the igloo.

Site Selection

Remote sites that would have the least effect on any surrounding igloo operations, off-post facilities, and greatest distance between the facility and off-post residential community were investigated. In order to insure minimal potential disruption of surrounding igloo operations, only pairs of igloos at the end of existing access routes were considered. The double door igloos on the east side of the North Igloo Area were determined to be located closer to other off-post facilities, thus eliminating them from consideration . All igloo pairs meeting the above listed criteria were determined to be qualitatively equal in distance from the off-post residential community. It was concluded that three (3) potential sites existed within the North Igloo Area for establishment of the NSCM Examination Facility, denoted as sites A, B, and C.

Terrain and Site Preparation

In an effort to limit overall cost, and civil facility costs in particular, an igloo pair with the relatively level terrain was an important factor in selecting the site. On-site accommodation of the treatment systems (Rapid Response System, Munitions Management Device One, and Munitions Management Device Two) will require a level area, approximately large enough to locate five (5) tractor trailers, adjacent to NSCM Examination Facility. The North Igloo Area in which the double door igloos are located has varying topography, with multiple ravines among the igloos. All three (3) potential sites that were evaluated have the area available to support location of the treatment systems; however, the site preparation required at each site varies significantly. It was concluded that the land to the west of the Site A igloo pair was basically level; therefore, the Site A igloo pair would have the lowest site preparation cost. Site B and Site C igloo pairs have similar surrounding topography and qualitatively equal site preparation cost.

Utility Availability

All potential sites will require upgrade of existing utility services. Utility upgrade cost was determined to be qualitatively equal for all potential sites.

NSCM EXAMINATION FACILITY CONCEPT OF OPERATIONS

Transportation, interim storage, transfer, unpacking and repacking, examination, and other ancillary operations will be conducted by trained chemical agent toxic materiel handlers, technicians, engineers, operators, and security personnel wearing appropriate levels of chemical personnel protective equipment.

Transportation

The overpacked recovered chemical warfare materiel items, stored in a high security chemical agent storage area, will be loaded into a transportation device and moved to the NSCM Examination Facility Interim Storage Igloo. In addition to functional required resources, the transportation convoy from the high security storage area to the secure NSCM Examination facility will include all necessary traffic

control and security escorts.

Interim Storage

The overpacked recovered chemical warfare materiel items will be stored in the Interim Storage Igloo while awaiting transfer to the Examination Igloo for examination, or awaiting transfer to a treatment device after examination, or awaiting transfer back to high security chemical agent storage area after examination. Overpacked recovered chemical warfare materiel items may also be depalletized and palletized as a part of interim storage operations.

Pre-Examination Transfer Operations

The overpacked recovered chemical warfare materiel items, stored in interim storage igloo, will be loaded onto a transfer device and moved from the interim storage igloo to the examination igloo. Upon entering the examination igloo the overpacked recovered chemical warfare materiel items will be placed in the main process room. The main process room will then be sealed off from the rest of the examination igloo prior to commencing unpack operations.

During unpacking, examination, and repacking operations: the primary containment room will be operated at negative pressure relative to the secondary containment main igloo structure, and the main igloo structure will be operated at negative pressure relative to the atmosphere.

Unpack Operations

Unpack operations will take place at the unpack/repack station located within the main process room. The overpacked recovered chemical warfare materiel will be logged into the data collection system to maintain accountability of the overpack container and contents throughout the examination process. The overpack container will then be manually opened and monitored for chemical agent. (If an anomaly occurs and chemical agent is detected, the individual recovered chemical warfare materiel items, within the multiple item overpack container will: First, be removed from the overpack container and placed in single item overpack containers. Second, the main process room and contents will be decontaminated. Following decontamination operations, operations will resume and follow their normal course, except individual leaking recovered chemical warfare materiel items will be examined in their single item overpack containers.) The main process room and process support area will be equipped with continuous agent monitoring capability to detect chemical agent during any step of the examination process.

Visual Inspection

After confirmation of negative chemical agent overpack container monitoring, the individual recovered chemical warfare materiel items within the overpack container will be transferred, one at a time, to an examination material handling fixture at the visual inspection station. The recovered chemical warfare materiel items will be visually inspected and results will be documented and entered into the data collection system. The individual recovered chemical warfare materiel items will then have permanent identification affixed to maintain accountability of each individual item.

Non-Intrusive Enhanced Examination

Following visual inspection, the individual recovered chemical warfare materiel items, located in the examination fixture, will be manually conveyed to the non-intrusive enhanced examination station. Each recovered chemical warfare materiel item will be examined utilizing radiographic and portable isotopic neutron spectroscopy (PINS) to determine mechanical, explosive, and fill configurations. Non-intrusive examination results will be documented and entered into the data collection system.

Repacking Operations

Upon completion of individual item examination operations, each recovered chemical warfare materiel item will be removed from the examination fixture, transferred to the pack/repack station, and packed in a single item overpack container. Each single item container will have a permanent identification affixed to maintain accountability of each individual item container. Individual single item overpack containers will be placed into the transfer device.

Post-Examination Transfer Operations

Upon completion of repacking operations, for all recovered chemical warfare materiel items contained in an overpack container, and confirmation of the agent free status of the main process room, the main process room materiel access doors will be opened to allow transfer equipment access. The overpacked recovered chemical warfare materiel items will then be transferred from the examination igloo to the interim storage igloo or on-site treatment system.

NSCM EXAMINATION FACILITY FEATURES

Existing Facilities

Two existing, adjacently located, munition storage igloos will be upgraded as a part of this project. Each igloo has a floor area of approximately 82 ft. long by 29 ft. wide, has a double door entrance in the front, and is earth covered.

Interim Storage Igloo

The interim storage igloo structure will receive minor upgrades, to include provisions for liquid containment and other general upgrades necessary to allow the execution of standard industry warehousing and material handling operations.

Examination Igloo

The examination igloo will be subdivided into two major functional areas: the main process room and the process support area. The main process room, which also provides primary liquid and vapor containment during chemical agent operations, will be the area in which all major process functions are conducted, including: unpacking, non-intrusive enhanced examination, and repacking. The process support area, which also provides secondary containment during chemical agent operations, will function as a safety observation area and staging area for main process room operations, will house the non-intrusive enhanced examination equipment, provide for storage of main process room material handling equipment when not in use, and provide for short term storage of operational consumables.

Both the main process room and the process support area will be equipped with continuous chemical agent monitoring and annunciation capability.

The examination igloo will be equipped with heating, ventilation and air-conditioning equipment. The heating and ventilating equipment will provide conditioned air to the main process room and the process support area to allow efficient operations by personnel wearing appropriate levels of chemical personnel protective equipment. The ventilation system will also include chemical agent containment capabilities through the use of cascaded negative pressures and an exhaust air filtration system incorporating proven filtration technology (i.e., multiple bed high efficiency particulate air and charcoal filers). The cascaded ventilation system will provide negative pressure in the main process room relative to the process support area (primary containment) and negative pressure in the process support area relative to the atmosphere external to the igloo (secondary containment) during chemical agent operations.

The main process room materiel access doors will allow direct placement of up to a "pallet sized" overpacked recovered chemical warfare materiel item directly into the main process room using a fork lift or pallet jack. The main process room will also be equipped with a personnel airlock for entry and egress by personnel during chemical agent operations. The personnel airlock will also serve as a primary decontamination station in the event that personnel egress might be required prior to decontamination of the main process room.

Main Process Room - Unpack/Repack Station

The unpack/repack station will be equipped to open the recovered chemical warfare materiel overpack containers, perform initial overpack container chemical agent and industrial safety monitoring, remove the recovered chemical warfare materiel from the overpack container, and transfer the recovered chemical materiel items to the visual inspection station. This will be accomplished manually using barrel handling and other material handling equipment. Necessary material handling fixtures and equipment will be provided to allow packing the recovered chemical warfare materiel items into single item overpack containers and placing the single item overpack containers into the transfer device.

Main Process Room - Visual Inspection Station

The visual inspection station will be an elevated observation and work platform to allow convenient visual inspection and placement of the recovered chemical warfare materiel items into the examination fixture.

Main Process Room - Non-Intrusive Enhanced Examination Station

The non-intrusive enhanced examination station will be an appropriately shielded appendage to the main process room allowing close placement of the examination equipment to the recovered chemical warfare materiel item. The actual non-intrusive examination equipment will be located outside the main process room, to prevent potential contamination of the equipment and ease of maintenance, and gain access to the recovered chemical materiel item through a fixed glass window or moveable vapor tight lens and boot. This station will be equipped with glove box ports to allow final positioning of the recovered chemical materiel item and examination fixture. This station will also be configured to allow isolation of this station. The isolation capabilities will simplify decontamination operations that might be necessary during other main process room operations. The facility will include the

capabilities to host the currently defined non-intrusive enhanced examination technologies (i.e., radiography and isotopic neutron spectroscopy). If required by future technological developments, the station configuration will include the inherent potential for substitution or addition of other examination equipment.

Site Control Complex

The site control complex will be a separate skid mounted portable structure and include the facility control room, supervisory and staff offices, meeting/break room, and sanitary facilities. The control room will house the necessary controls to monitor all NSCM Examination Facility operations, including interim storage igloo, examination igloo, and general facility functions.

Personnel Decontamination Building

The personnel decontamination building will be a separate portable structure which will provide secondary decontamination of personnel and personnel protective equipment if exposed to chemical agents and industrial chemicals. The facility will be equipped with standard and specialized heating, ventilation and air-conditioning equipment. The ventilation system will include chemical agent containment capabilities through the use of an exhaust air filtration system. This facility would also serve as the industrial shower facility during normal operations.

Utilities

The NSCM Examination Facility will be a self sufficient facility utilizing commercial and site specific utilities for normal operations. Emergency backup systems will be provided for all safety related functions. An emergency electrical power generator and uninterruptable power supply will provide electrical power for all essential loads (e.g., controls, monitoring, decontamination, and ventilation systems) as necessary to allow for orderly shutdown of operations in the event of the loss of commercial electrical power. The generator will be a packaged and skid mounted unit located adjacent to the examination igloo. Potable water, process water, and sanitary sewer will be provided by self-contained site specific systems.

Communications

Commercial and intra-installation telephone services will be supplied to the facility to allow access to other operating elements as a part of normal operations. As an emergency backup to telephone communications, radios would be used to allow continuous communication in the event of telephone system failure. Site communications will include intrinsically safe mobile radios and/or an explosion proof fixed intercom system to allow intra-site communications between all operating elements and facilities (e.g., control room, interim storage igloo, examination igloo, personnel decontamination facility, transportation and transfer crews, maintenance personnel).

BOTTOM LINE

Since initial production began in 1942, Pine Bluff Arsenal has continuously supported American defense efforts through the capable production of conventional and chemical munitions, effective maintenance of chemical and biological defensive equipment, safe storage of conventional and chemical warfare materiel, proactive remediation of installation industrial facilities and sites, and safe demilitarization of conventional munitions and chemical warfare materiel.

The NSCM Examination Facility construction and operations will be accomplished by a highly trained team comprised of both government and contractor personnel. Construction and operational efficiencies will be recognized by establishing a self-sufficient facility with the potential to host planned on-site treatment systems.

The NSCM Examination Facility at Pine Bluff Arsenal will enhance the Army's responsiveness and provide life-cycle management capability for recovered chemical warfare materiel.

UXO FORUM 1996
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